

Ionic Ratios of Some of the Major Components in River-Diluted Sea Water in Bute and Knight Inlets, British Columbia¹

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ABSTRACT

The variation in the K^+/Na^+ and Ca^{++}/Na^+ ratios in highly diluted sea waters near the heads of two British Columbia inlets has been determined flame photometrically. Although the values agree in general with those calculated from the effect of dilution, discrepancies larger than the analytical error appear. These discrepancies may be explained by cation exchange processes taking place where the silt suspended in the river meets the sea.

INTRODUCTION

GENERAL

ONE of the important results of Dittmar's (1884) analysis of sea water samples collected by the *Challenger* from all the oceans was the conclusion that the relative concentrations of the major dissolved constituents were constant regardless of the source of the sea water. The salinity of a sample can, therefore, be calculated if the concentration of one of the major components is determined experimentally. Using water from the Baltic Sea, Knudsen (1901) obtained the empirical relation

$$S = 0.030 + 1.8050 Cl$$

between the salinity, S , and the chlorinity, Cl . It has since become standard practice to specify the salinity of a sample from a determination of its chlorinity, usually expressed as parts per thousand (‰) by weight.

This procedure has been amply verified for high-chlorinity samples. For example, Robinson and Knapman (1941) found a value for the Na/Cl ratio in the northeastern Pacific Ocean of 0.5556 ± 0.001 in agreement with Webb's (1939) value for the Firth of Clyde. Thompson and Wright (1930) demonstrated the constancy of the Ca/Cl and Mg/Cl ratios in the northeastern Pacific.

The relative constancy of composition so characteristic of the open ocean is apparently not maintained in certain enclosed areas. Gripenberg (1937) identified four different water masses in the Baltic Sea and the Gulf of Finland from the variation in the Ca/Cl ratio. Lyman and Fleming (1940) have pointed out that "in any specific locality where dilution by river water occurs, water of a given chlorinity will not necessarily have the same properties as water of the same

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chlorinity obtained by diluting oceanic water with distilled water nor water corresponding to that of Knudsen's Tables". Although it has been recognized in a general qualitative sense that land drainage affects the relative composition of sea water, no detailed quantitative estimate nor experimental evaluation of the effect of dilution by rivers on the major cation components of sea water has appeared.

With the increase in interest in the oceanography of coastal regions, it is necessary to understand what limitations to the classical constancy of the relative composition of sea water exist. In brackish water near land, the relative composition should depend on that of the water that drains into the sea. Rivers are generally relatively richer in calcium and potassium than is the ocean as shown in Table I taken from Sverdrup *et al.* (1946, p. 214). Therefore, the ionic ratios in river-diluted sea water cannot be expected to be the same as in oceanic water.

TABLE I.—Percentage composition of dissolved solids in river and sea water. (From Sverdrup *et al.* (1946, p. 214).)

Ion	River water (weighted average)	Sea water
	%	%
CO ₃ ²⁻	35.15	0.41
SO ₄ ²⁻	12.14	7.68
Cl ⁻	5.68	55.04
NO ₃ ⁻	0.90	...
Ca ⁺⁺	20.39	1.15
Mg ⁺⁺	3.41	3.69
Na ⁺	5.79	30.62
K ⁺	2.12	1.10
(Fe, Al) ₂ O ₃	2.75	...
SiO ₂	11.67	...
Sr ⁺⁺ , H ₂ BO ₃ , Br ⁻	...	0.31

These considerations form the basis of the problem. The present work establishes the magnitude of the variation of the ionic ratios near some British Columbia estuaries. The sodium, potassium and calcium in river-diluted sea water near the heads of two British Columbia inlets (Bute and Knight) have been determined in samples collected in the summers of 1952 and 1953. The alkalinity of the latter samples was also determined and will be reported later.

ANALYTICAL METHODS

Determinations of the concentrations of the most abundant cations in sea water have been made many times in the past. The methods used in analysis of sea water were reviewed in detail by Thompson and Robinson (1932). They gave average values of 0.02174, 0.02000 and 0.5509 respectively for the weight ratios Ca/Cl, K/Cl and Na/Cl. In the early investigations gravimetric methods were used. Calcium was precipitated (two or three times to minimize coprecipitation) as the oxalate and potassium as the chloroplatinate. Sodium was often determined indirectly. After evaporating a sample to dryness with dilute sulphuric acid and determining the calcium, potassium and magnesium gravimetrically, the sodium concentration was obtained by difference. More recently

Lyman and Fleming (1940) collected the available data on the composition of sea water. As "best values" of the Ca/Cl, K/Cl and Na/Cl ratios they chose 0.02106, 0.0200 and 0.5556 respectively.

Shortly thereafter Robinson and Knapman (1941) determined sodium directly in 99 samples of water from the northeast Pacific. They used a gravimetric method based on the precipitation of sodium with zinc uranyl acetate. They obtained an average value for the Na/Cl ratio of 0.5556 ± 0.001 in exact agreement with that calculated earlier by Lyman and Fleming (1940) and consistent with Webb's (1939) directly determined value.

The concentration of potassium in sea water was carefully determined by Webb (1939). He precipitated the potassium as the double cobaltinitrite of potassium and silver, and titrated the precipitate with standard ceric sulphate. His value for the K/Cl ratio in the Firth of Clyde was 0.02009 ± 0.0002 .

Of the new reagents that have recently been used for the determination of potassium in various materials, sodium tetraphenylborate appears the most promising for sea water analysis. Since Raff and Brotz (1951) introduced the reagent, Gloss (1953) has reviewed the early literature and Flaschka *et al.* (1953, 1955) and others have made many improvements in the analytical procedure.

Thompson and Wright (1930) determined calcium gravimetrically, using three precipitations of the oxalate to obtain their value of 0.02150 for the Ca/Cl ratio in the northeastern Pacific. Following Webb's (1938) suggestion that the strontium and calcium in sea water were chemically indistinguishable, Lyman and Fleming (1940) recalculated Thompson and Wright's (1930) value and obtained 0.02106 for the Ca/Cl ratio. De Sousa (1953, 1954) has applied the complexometric titration with disodium ethylenediamine tetraacetate to the determination of calcium and magnesium in sea salt, brine and sea water, but has not reported any specific values for the Ca/Cl ratio.

Although new reagents have simplified the determination of potassium and calcium by classical gravimetric and volumetric methods, no corresponding specific reagent for sodium has been found. The estimation of sodium has, however, been greatly facilitated by the development of flame photometry. Since the early reports of Barnes *et al.* (1945) and Berry *et al.* (1946) several commercial instruments have become available, and flame photometry has become increasingly popular for the determination particularly of sodium and potassium in various materials. West *et al.* (1950) described the use of "radiation buffers" in the flame photometric determination of sodium, potassium and calcium in river water to reduce the mutual interference of these three metals and of magnesium. Lundgren (1953) investigated the factors affecting the determination of the same cations separately and in aqueous saline solutions. He confirmed the conclusion of Bills *et al.* (1949) that the mutual interference of sodium and potassium is decreased by working at low concentration.

Flame photometric methods have recently been applied to the analysis of sea water. Smales (1951), Odum (1951) and Chow and Thompson (1955a) have determined the strontium content of sea water. Chow and Thompson (1955b)

have determined the value of the Ca/Cl ratio to be 0.02184, which agrees with the earlier gravimetric value of Thompson and Wright (1930), and indicates that Webb's (1939) assumption that strontium interfered with the gravimetric estimation of calcium was apparently incorrect. Using a flame photometer, Shanklin (1954) found that the concentrations of sodium and potassium in sea water drawn from the Woods Hole, Massachusetts, pumping station were respectively 534.0 and 18.2 millimoles per liter (the value for potassium especially is unusually high).

Although some doubt still remains concerning the exact value of the concentrations of some of the major components in sea water, this uncertainty does not affect the present study. It is concerned with *changes* in the ratios of the concentration of the major components, and these changes are here determined by direct comparison of river-diluted sea water samples with diluted standard sea water (both natural and synthetic). Further, the analytical method used is shown to be accurate to well within 3% for the K/Na and Ca/Na ratios. Hence the conclusions will be modified only to a slight degree by changes in the absolute values of the concentrations of the major components in sea water of a given chlorinity.

EXPERIMENTAL

APPARATUS

Because of the speed with which flame photometric determinations can be made and the possibility of using a flame photometer on shipboard, the applicability of the flame photometric determination of sodium, potassium and calcium to sea water was tested. A Beckman model DU spectrophotometer and flame attachment (Beckman No. 9200) with an acetylene-oxygen burner was used. The principle and operating instructions of the instrument are described in a Beckman Instrument Inc. publication (1951). For the determination of calcium, the instrument was fitted with its photomultiplier attachment. Without this accessory, the flame background (caused by the sodium) was too intense to permit the precise determination of calcium at the required slit width. The increased sensitivity of the photomultiplier tube permitted the use of narrower slits and smaller sodium backgrounds were obtained when calcium was determined. Potassium was determined at a wave-length of 768m μ , sodium at 589m μ , and calcium at 423m μ .

PROCEDURE

To make a determination, the brackish water sample was diluted, if necessary, so that its sodium concentration fell into the range 100 to 700 p.p.m. From the known chlorinity the approximate sodium concentration was estimated. Standard solutions with sodium concentrations that lay close to and on either side of the unknown were chosen. Readings of relative flame intensity of the standards were alternated with those of the sample to minimize the effect of fluctuations in the atomizer-burner. At least three sets of readings were taken at each wave-length and the concentration of each component in the diluted sample was calculated by linear interpolation between the standards.

Calibrated volumetric glassware was used in the preparation of all standard solutions. The need for standard solutions that approximate the samples in composition in accurate flame photometric determinations was suggested by Porter and Wyld (1955) among others. The standard solutions required were prepared by dilution with distilled water of both high-chlorinity natural sea water and synthetic sea water, and were stored in glass or polyethylene bottles. Fresh standards were prepared from time to time during the course of the work. Whenever this was necessary, the flame intensities of the "fresh" and "old" standards were compared, and it was invariably found that they agreed with one another at the various wave-lengths of interest. Standards in the range 80 to 200 p.p.m. Na stored in glass bottles for 8 months gave the same flame intensities at 589, 768 and 423m μ as freshly prepared standards stored in polyethylene bottles.

The synthetic sea water was prepared according to the formula of Brujewicz (1931). The calcium chloride and magnesium chloride were supplied by equivalent amounts of pure calcium carbonate and magnesium oxide dissolved in a minimum quantity of hydrochloric acid, the small excess being precipitated with silver oxide and removed by filtration. This solution contains the correct concentrations of the major components except calcium. It was used only in the determination of sodium and potassium.

Since the most reproducible results were obtained when the sodium concentration fell in the range 30 to 700 p.p.m., a series of standard solutions covering this range (in 10-p.p.m. steps at the lower values, and 100-p.p.m. steps at higher values) was prepared by dilution. At concentrations above 700 p.p.m. sodium, the atomizer-burner clogged frequently. Below 100 p.p.m. sodium, other difficulties were encountered. Use of the more dilute standards required great dilution of many of the samples of interest. At the low concentration of potassium then prevailing, adsorption effects became appreciable. The volumetric flasks used for dilution needed extensive rinsing to eliminate traces of potassium that would contaminate the next sample diluted in them. At potassium concentrations higher than 4 p.p.m. (corresponding to a sodium concentration of about 100 p.p.m.), adsorption effects were less troublesome, and many of the samples could be analyzed without dilution.

COLLECTION OF SAMPLES

Samples of water were collected at various depths in Bute and Knight Inlets in the summers of 1952 and 1953 at stations about 5 miles apart shown in Fig. 1 and 2. Close to the heads of the inlets, samples were also taken near each bank. The chlorinities of the samples were determined immediately by the Mohr titration using silver nitrate standardized against Copenhagen Normal Sea Water. Samples of chlorinity less than 2‰ were retained in either glass or polyethylene bottles for subsequent examination ashore. Samples were also retained from the Klinaklini River at the head of Knight Inlet and from the Homathko and Southgate Rivers at the head of Bute Inlet. These samples were collected from the surface of the rivers about ½ mile up from their mouths, where rapid river outflow

was very evident. The Southgate is smaller than the Homathko and presumably does not affect the composition of the water at the head of Bute Inlet as much as the latter does. During the cruises, some of the water samples were analyzed for sodium, potassium and calcium with the flame photometer on shipboard. The chlorinity of the samples retained was redetermined ashore, and the concentrations of sodium, potassium and calcium were determined by the procedure outlined.

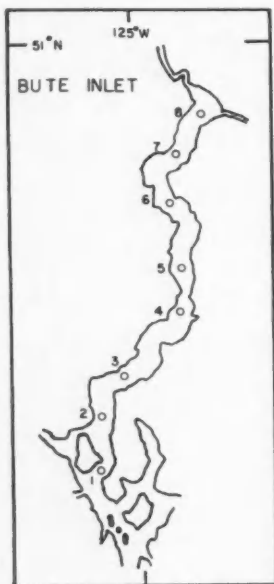


FIG. 1.—Stations in Bute Inlet.

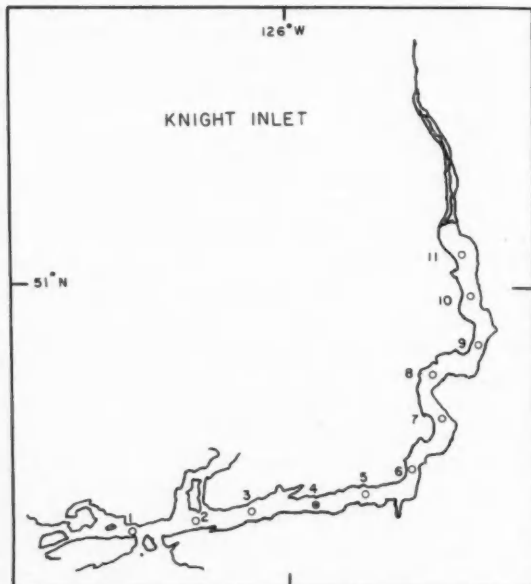


FIG. 2.—Stations in Knight Inlet.

RESULTS AND DISCUSSION

ACCURACY

To obtain an indication of the accuracy of the flame photometric determinations, sodium and potassium were determined in some samples provided by Dr. G. L. Pickard of the Institute of Oceanography, University of British Columbia. These samples had been collected near the head of Bute Inlet in the early spring of 1952 when the river flow was slight. Some typical results are listed in Table II. The average values of the Na/Cl, K/Cl and Ca/Cl ratios in sea water are given by Lyman and Fleming (1940) as respectively 0.5556, 0.02000 and 0.02106. The ratios of K/Na and Ca/Na should then be 0.03600 and 0.03791 respectively. The percentage deviation of the observed value is listed in the last column of Table II. The chlorinities of the samples are sufficiently high for the ionic ratios to be essentially the same as in sea water (see below). Table II

shows that an accuracy of about 2% or better may be expected in the values of the K/Na ratios. The uncertainty in the Ca/Na ratios is also about 2%.

TABLE II.—Typical sodium and potassium determinations in high-chlorinity samples collected in Bute Inlet, Spring 1952.

Chlorinity	Na ⁺ concn.	K ⁺ concn.	100 $\frac{K^+}{Na^+}$	Deviation from Lyman & Fleming's value*
$\%$	<i>p.p.m.</i>	<i>p.p.m.</i>		$\%$
11.15	6080	219	3.61	0
7.82	4215	155	3.67	+2
7.20	3845	138	3.58	-1
10.04	5570	203	3.64	+1

*Lyman and Fleming (1940) give $\frac{K^+}{Na^+} = 0.03600$.

ANALYSIS OF RIVER WATERS

Since the composition of the rivers flowing into the inlets determines the composition of the water close to their heads, river water samples were analyzed for sodium, potassium, calcium and chloride. Dilute solutions of the chloride of each metal were used as standards. In these dilute solutions, the mutual interference in flame photometric determinations is negligible (Lundgren, 1953). The results of the analyses of the river samples taken in both 1952 and 1953 are indicated in Tables III and IV. The sodium concentration in the samples collected from the rivers was very low in both years.

TABLE III.—Ionic concentrations in samples of river water collected in 1952.

River	Date	Na ⁺	K ⁺	Ca ⁺⁺	Cl ⁻
		<i>p.p.m.</i>	<i>p.p.m.</i>	<i>p.p.m.</i>	<i>p.p.m.</i>
Homathko	Aug. 4	0.1	1.10	2.79	1.52
Southgate	Aug. 4	0.1	1.04	1.95	1.04
Klinaklini	Aug. 6	0.1	1.11	2.72	1.77

TABLE IV.—Ionic concentrations in samples of river water collected in 1953.

River	Date	Na ⁺	K ⁺	Ca ⁺⁺	Cl ⁻
		<i>p.p.m.</i>	<i>p.p.m.</i>	<i>p.p.m.</i>	<i>p.p.m.</i>
Homathko	July 20	0.1	1.44	3.92	2.02
Klinaklini	July 16	0.1	1.73	3.13	1.76

CALCULATION OF EFFECT OF DILUTION

To calculate the variation expected as a result of mixing sea water with fresh water, consider that A parts of sea water of chlorinity = $a\%$ is mixed with B parts of river water of chlorinity = $b\%$. In the resulting mixture

$$Cl\% = \frac{Aa + Bb}{A + B} \quad (1)$$

If the concentration of sodium ion in sea water is c and in river water is d , then in the mixture

$$[\text{Na}^+] = \frac{Ac + Bd}{A + B}.$$

If the concentration of potassium ion in sea water is e and in river water f , then in the mixture

$$[\text{K}^+] = \frac{Ae + Bf}{A + B}.$$

In undiluted sea water the ratio

$$\frac{[\text{K}^+]}{[\text{Na}^+]} = \frac{e}{c},$$

in river-diluted sea water,

$$\frac{[\text{K}^+]}{[\text{Na}^+]} = \frac{Ae + Bf}{Ac + Bd},$$

and the fractional increase of the ratio in such water is

$$\Delta \left(\frac{[\text{K}^+]}{[\text{Na}^+]} \right) = \frac{\frac{Ae + Bf}{Ac + Bd} - \frac{e}{c}}{\frac{e}{c}} = \frac{B(cf - de)}{e(Ac + Bd)}.$$

In the special case where the concentration of sodium ion in the river is extremely small, the terms de and Bd are small compared with cf and Ac respectively, and the expression may be approximated by

$$\Delta \left(\frac{[\text{K}^+]}{[\text{Na}^+]} \right) = \frac{B}{A} \times \frac{f}{e}.$$

From equation (1) it follows that the dilution factor

$$\frac{B}{A} = \frac{a - \text{Cl}}{\text{Cl} - b}.$$

The fractional increase in the K/Na ratio becomes

$$\Delta \left(\frac{[\text{K}^+]}{[\text{Na}^+]} \right) = \frac{a - \text{Cl}}{\text{Cl} - b} \times \frac{f}{e}. \quad (2)$$

If dilution is the only process that contributes to the change in the K/Na ratio in brackish water, values calculated according to equation (2) should agree with those observed experimentally. A corresponding expression may be used to calculate the expected increase in the Ca/Na ratio.

In the river samples collected in 1952, the concentration of sodium was very small, as shown in Table III. Equation (2) should be applicable to the calculation of the change in ionic ratios resulting from dilution with river water. Since the Southgate River is smaller than the others, for simplicity its effect may be neglected, and the increase in the ionic ratios in Bute Inlet should be

nearly the same as in Knight Inlet. On this basis, values for the expected increase in the ionic ratios above their oceanic values have been calculated and are shown in Table V. In these calculations, the chlorinity of sea water and its potassium and calcium concentrations were taken respectively as 19.00‰, 380 p.p.m. (Sverdrup *et al.*, 1946, p. 173) and 415 p.p.m. (calculated from Chow and Thompson, 1955b). (If the base chlorinity of Georgia Strait and the inlets draining into it is taken as 17‰, the values in Table V would be increased by about 0.1% only.) The potassium and calcium concentrations in the river water are taken as 1.10 and 2.75 p.p.m., the average of the values for the Homathko and Klinaklini Rivers listed in Table III.

TABLE V.—Calculated increase in ionic ratios in waters of Bute and Knight Inlets, 1952.

Chlorinity	$\Delta(K/Na)$ Increase	$\Delta(Ca/Na)$ Increase
‰	‰	‰
10.00	0.3	0.6
5.00	0.8	1.9
2.00	2.5	5.6
1.00	5.2	11.9
0.50	10.7	24.5
0.10	54.7	126

SHIPBOARD RESULTS

To test the reliability of the flame spectrometric equipment on board ship, some determinations were made during the sample-collecting cruises. During these determinations, the ship (C.N.A.V. *Ehkoli*) was proceeding at 8 knots in a smooth sea and was rolling slightly. The spectrophotometer was placed directly on an ordinary laboratory bench to which the cylinders of acetylene and oxygen were chained. Since the required power for the instrument is supplied by a storage battery, the only ship service used was the 110-volt a-c. line to operate the battery charger. In general, facilities in the ship's laboratory compared favorably with those available ashore with the obvious qualification that the vibration present in the ship was absent ashore.

Some of the shipboard results are compared in Table VI with those obtained ashore on the same samples. Since there is no significant difference between the two sets of values, the Beckman DU spectrophotometer and flame attachment may apparently be used with confidence on shipboard under the conditions mentioned.

TABLE VI.—Comparison of determinations on shipboard and ashore.

Chlorinity	Na ⁺		K ⁺		$\frac{K^+}{Na^+}$	
	Ship	Ashore	Ship	Ashore	Ship	Ashore
‰	p.p.m.		p.p.m.			
0.627	344	343	13.2	12.9	0.0384	0.0376
0.976	535	537	19.6	19.8	0.0366	0.0368
1.281	710	710	26.1	26.1	0.0368	0.0368

STORAGE OF SAMPLES

Most of the samples collected in 1952 and all those collected in 1953 were stored in 250-ml. screw-capped polyethylene bottles; the remainder were stored in glass-stoppered bottles. The sodium and potassium in some of the samples collected in 1952 were determined immediately on shipboard. In all the samples collected that year, the sodium and potassium were determined within 6 weeks after collection. No significant change in the concentration of either ion was detected during this period in those samples analyzed both on shipboard and in the laboratory. The determination of calcium in these samples was begun in May, 1953, when the photomultiplier attachment to the spectrophotometer was acquired. Because of the long time that had elapsed, potassium and sodium were redetermined in some of the samples. No significant change in the concentration of either ion was detected, and it was therefore assumed that the calcium concentration determined at this time closely approximated that which existed in the samples at the time of collection.

The sodium, potassium and calcium were determined in the samples collected in 1953 within 7 weeks of the time of collection. In those samples that had been analyzed on shipboard, no significant change in the concentration of any of the ions was detected during this time.

Exchange processes involving the silt contained in some of the samples is not likely to affect the concentrations of the various ions over the long time of storage. Alexander and Johnson (1949, p. 726) declare that equilibrium is reached almost instantaneously in non-zeolitic clays, whereas many hours may be required in zeolites. Equilibrium had presumably been reached in the 1952 samples before the first laboratory determinations were made and it should not have been upset by continued storage.

IONIC RATIOS

The results of the determinations of the sodium, potassium and calcium in the low-chlorinity samples collected near the heads of the inlets in 1952 and 1953 are listed in Tables VII and VIII respectively. Station numbers listed correspond to those in Figs. 1 and 2, those in Bute Inlet being designated by Bu and those in Knight Inlet by Kn. Stations with suffixes R and L were close to the west and east banks respectively. The depth from which each sample was taken is given in yards, followed by its chlorinity in ‰. Most of the ionic concentrations tabulated are the average of two or three sets of determinations.

In Tables VII and VIII the concentrations of potassium and calcium are expressed as their "sodium-equivalent" in p.p.m., defined as follows. Since the standard solutions used in the determinations were prepared by dilution of oceanic water or synthetic sea water with distilled water, the ionic ratios in all the standards are the same as in sea water. The over-all composition of any of the standards may therefore be designated by its sodium concentration. The potassium or calcium concentration of an unknown may be specified by the sodium concentration of a standard solution that would have the same potassium or calcium concentration as the unknown. This is referred to as the "sodium-

TABLE VII.—Ionic concentrations observed in the waters of Bute and Knight Inlets, 1952.

Station	Date	Depth	Chlorinity	Na ⁺ concn.	K ⁺ concn. (Na ⁺ equiv.)	Ca ⁺⁺ concn. (Na ⁺ equiv.)	K ⁺ Na ⁺ Increase	Ca ⁺⁺ Na ⁺ Increase
		yd.	‰	p.p.m.	p.p.m.	p.p.m.	%	%
Bu-4	Aug. 4	0	2.08	1153	1186	1207	3	5
		1	2.10	1168	1196	1202	3	3
		2	3.33	1868	1881	1868	1	0
Bu-5	Aug. 4	0	1.97	1053	1087	1088	3	3
		1	2.17	1198	1227	1224	2	2
		2	4.44	2526	2551	2587	1	-2
Bu-6	Aug. 4	3	6.41	3628	3648	3560	1	6
		0	1.28	700	722	739	3	3
		1	2.74	1506	1547	1545	3	3
Bu-7R	Aug. 5	2	3.69	2085	2123	2097	2	1
		0	0.92	503	515	592	3	18
		2	0.92	503	523	591	4	18
Bu-7	Aug. 4	3	0.97	535	547	619	2	17
		4	1.00	556	571	636	3	15
		6	2.77	1550	1572	1622	1	4
Bu-7L	Aug. 5	0	0.63	343	358	424	4	24
		1	0.61	336	352	412	7	23
		2	0.63	347	356	415	3	20
Bu-8R	Aug. 5	3	0.63	342	352	423	3	24
		0	0.98	537	547	598	2	11
		1	1.42	783	785	829	0	6
Bu-8	Aug. 4	2	1.65	917	934	963	2	5
		4	2.86	1567	1575	1590	1	2
		0	0.48	260	281	346	8	34
Bu-8L	Aug. 5	2	0.50	273	289	356	6	30
		3	0.52	283	295	360	4	27
		4	0.73	402	415	465	3	16
Bu-8	Aug. 4	6	2.30	1207	1246	1279	3	6
		0	1.17	649	663	714	2	10
		1	1.22	668	676	721	1	7
Bu-8L	Aug. 5	2	2.57	1419	1443	1460	2	3
		0	0.32	174	190	266	9	53
		2	0.44	237	260	319	10	39
Kn-6	Aug. 6	3	0.62	338	358	411	6	22
		4	0.64	354	378	420	7	19
		6	6.37	3541	3578	3537	1	0
Kn-7	Aug. 6	0	1.57	869	887	904	2	4
		2	1.87	1039	1058	1084	2	4
		4	3.47	1851	1889	1930	2	4
Kn-8	Aug. 6	0	0.84	460	480	547	4	19
		2	0.83	457	480	551	5	20
		4	0.85	462	483	550	4	19
Kn-8	Aug. 6	6	4.52	2328	2380	2409	5	4
		0	0.43	231	243	314	5	36
		2	0.43	228	249	320	4	35
Kn-9	Aug. 6	4	0.48	258	272	340	5	31
		6	1.26	696	709	731	2	5
		0	0.37	203	227	314	12	54
Kn-10R	Aug. 7	2	0.37	200	227	299	13	50
		4	0.34	188	209	286	11	52
		6	0.40	215	243	309	12	44
Kn-10	Aug. 6	0	0.16	85	108	145	29	71
		2	0.23	123	148	190	20	55
		4	0.36	193	218	298	13	52
Kn-10L	Aug. 7	6	0.84	460	475	549	3	19
		8	6.58	3480	3510	3630	1	4
		0	0.25	133	158	223	19	68
Kn-11R	Aug. 7	2	0.25	132	158	213	20	62
		4	0.26	136	161	224	19	65
		6	0.27	149	172	238	16	59
Kn-11L	Aug. 7	8	1.35	747	762	766	2	2
		0	0.28	152	176	241	16	62
		2	0.31	165	179	257	8	55
Kn-11	Aug. 6	4	0.34	183	202	277	10	53
		6	0.38	206	228	303	11	47
		8	14.60	8230	8180	7990	-1	-3
Kn-11R	Aug. 7	13	15.83	8980	8990	8950	0	0
		0	0.14	75	117	149	56	98
		2	0.21	112	146	186	31	66
Kn-11L	Aug. 7	4	0.21	114	147	194	29	70
		6	0.37	108	228	299	15	50
		8	2.09	1160	1190	1210	2	4
Kn-11	Aug. 6	0	0.15	80	108	154	36	94
		2	0.15	79	113	158	42	99
		4	0.20	104	136	175	31	68
Kn-11L	Aug. 7	6	0.52	282	301	387	7	38
		0	0.14	71	91	151	29	113
		2	0.15	79	101	151	27	90
Kn-11L	Aug. 7	4	0.15	81	117	159	44	95
		6	0.19	99	128	184	30	87
		8	9.88	5490	5590	5550	2	1

TABLE VIII.—Ionic concentrations observed in the waters of Bute and Knight Inlets, 1953.

Station	Date	Depth	Chlorinity	Na ⁺	K ⁺ concn.	Ca ⁺⁺ concn.	K ⁺	Ca ⁺⁺
				concn.	(Na ⁺ equiv.)	(Na ⁺ equiv.)	Na ⁺	Na ⁺
							Increase	Increase
		yd.	‰	p.p.m.	p.p.m.	p.p.m.	%	%
Bu-6	July 20	0	0.96	519	541	590	4	16
		2	1.07	592	645	616	9	4
Bu-7R	July 21	0	0.12	61	94	134	56	122
		2	0.24	128	166	209	30	64
Bu-7	July 21	0	0.12	61	101	134	65	119
		2	0.26	137	165	206	21	51
Bu-7L	July 21	0	0.16	96	131	170	37	78
		2	0.35	188	220	282	17	50
Bu-8R	July 21	0	0.17	87	121	170	42	96
		2	0.25	151	199	271	31	79
Bu-8	July 21	0	0.14	80	122	146	53	83
		2	0.21	119	155	186	30	67
Bu-8L	July 21	0	0.18	100	138	165	39	66
		2	0.20	105	142	158	35	51
Kn-7	July 16	0	0.42	229	264	289	15	31
		2	1.10	602	611	664	2	10
Kn-8	July 16	0	1.34	715	742	...	4	...
		2	2.31	1247	1255	1292	1	4
Kn-9R	July 17	0	0.82	529	546	605	3	14
		2	1.09	594	600	656	1	11
Kn-9	July 16	0	0.57	309	322	400	4	30
		2	0.60	311	328	396	5	27
Kn-9L	July 17	0	0.63	387	401	465	4	20
		2	0.71	396	412	473	4	20
Kn-10R	July 17	0	0.90	518	533	614	3	19
		2	0.71	400	406	468	2	17
Kn-10	July 16	0	0.71	398	411	476	3	19
		2	0.71	398	415	478	4	20
Kn-10L	July 17	0	0.46	245	261	356	14	37
		2	0.50	273	290	372	7	27
Kn-11R	July 17	0	0.76	419	446	503	6	20
		2	0.53	283	301	381	6	35
Kn-11	July 16	0	0.58	307	332	406	8	32
		2	0.78	418	438	493	5	18
Kn-11L	July 17	0	0.43	231	253	330	10	43
		2	0.50	275	286	355	4	29
Kn-12	July 17	0	0.63	351	367	424	5	21
		2	0.47	246	287	354	17	44
Kn-13	July 17	0	0.75	413	441	499	7	21
		2	1.17	638	650	707	2	11
Kn-14	July 16	0	0.95	516	538	612	4	19
		2	0.99	552	561	635	2	15
Kn-15	July 17	0	0.47	241	262	344	9	43
		2	0.48	248	263	354	6	43
Kn-16	July 17	0	0.74	399	424	502	6	31
		2	0.74	399	424	502	6	31

equivalent" of the potassium or calcium concentration. The actual concentrations of potassium and calcium may be obtained from their sodium-equivalents by multiplying the latter by the K/Na and Ca/Na ratio respectively in oceanic water, viz. 0.03600 and 0.0379 (from values of Lyman and Fleming, 1940), or accepting the recent value of Chow and Thompson (1955b), the calcium concentration (in p.p.m.) may be obtained from its sodium equivalent by multiplying by 0.0394. In high-chlorinity sea water, the values of the sodium-equivalents of both potassium and calcium are the same as the sodium concentration in the

sample. In the river-diluted waters, the increase in the ionic ratio of potassium to sodium is calculated as follows:

$$\% \text{ Increase} = \frac{100 (\text{sodium-equivalent of potassium} - \text{sodium concentration})}{\text{sodium concentration}}$$

Expressing the potassium and calcium concentrations as their sodium equivalents has two advantages. Only in samples in which the K/Na ratio differs from that of sea water is there any difference between the values of the sodium concentration and the sodium-equivalent of potassium. Further, the observed *increases* in the ionic ratios are in fact independent of the absolute values of the concentrations of the individual abundant components of sea water, and this independence is emphasized by this method of expressing the concentrations of the ions.

In Table VII are included some results obtained with fairly high-chlorinity sea water samples. In them (e.g. Bu-8L-10yd., Kn-10L-8 and 13 yd., Kn-11L-8yd.) only small increases or decreases in the ionic ratios were observed. Only in one sample (Kn-10L-8yd.) was the observed ionic ratio as much as 3% different from its value in the standards; in the other high-chlorinity samples the observed ionic ratios were more nearly the same as in the standards. The good agreement between the observed and expected values of the ionic ratios in these samples shows that the dilute standard solutions used were suitable for the determinations, and places an upper limit of 3% on the error of a single determination.

The increase in the ionic ratios in the 1952 samples having chlorinities less than 1‰ is plotted in Fig. 3. The ionic ratios in the samples collected in 1953 show a similar distribution. The curves are drawn through values for the ionic ratios calculated by equation (2) and listed in Table V. The experimental points follow the calculated curves generally, indicating that simple dilution of sea water by river water is an important process that contributes to the observed increase in the ionic ratios in these samples. However, the analytical error (3% maximum) is too small to account for the scattering of most of the experimental points from the calculated curves. Most of the K/Na points lie below the calculated curve and the Ca/Na points lie above it.

The discrepancy between the experimental and calculated values implies that processes other than simple mixing of river water with sea water occur at the heads of the inlets. At least three other processes may contribute to this difference.

(a) The sea water may suffer appreciable dilution by fresh water from some source other than the rivers at the heads of the inlets. Since rain contains lower concentrations of dissolved salts than does river water (Bertrand, 1945, found 20γ K per litre in rain near Paris), appreciable direct precipitation should make the observed ionic ratios lower than those calculated. Both the K/Na and Ca/Na ratio should be decreased, however, and since this was not observed, the effect of rain alone cannot account for the discrepancy. If an appreciable quantity of ground water that is more dilute than the rivers finds its way into the inlets,

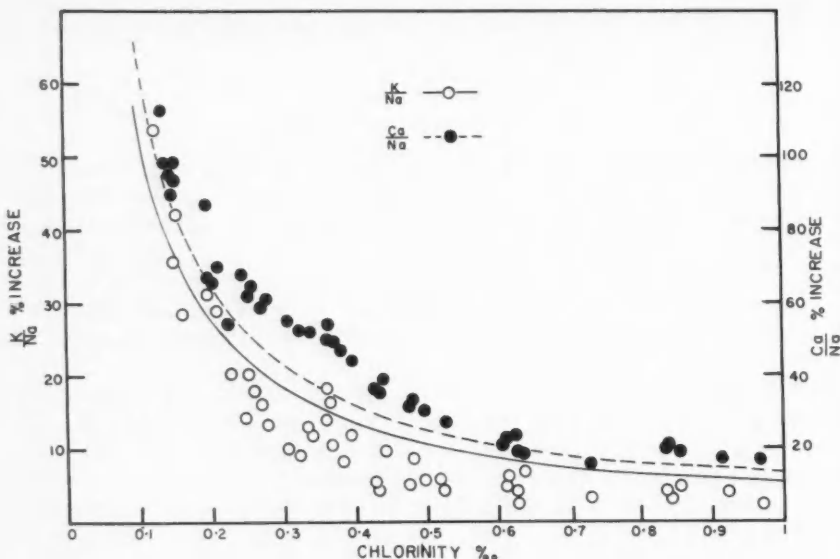


FIG. 3.—Ionic ratios in samples collected near the heads of Bute and Knight Inlets, 1952. The curves are drawn through points calculated from Equation (2), page 280.

the ionic ratios should also be lower than those calculated. Again, however, unless the ground water is considerably richer in calcium and poorer in potassium than the rivers, the effect of ground water alone cannot explain the observed values of the ionic ratios.

(b) Potassium-ion may have been adsorbed by the bottles in which samples were stored. This suggestion too may account for the observed K/Na ratio, but not for the Ca/Na ratio. Further, no significant change in the potassium-ion concentration was observed in those samples in which it was determined immediately after collection on shipboard, 1 to 6 weeks later in the laboratory, and again 9 months later.

(c) A small amount of cation exchange may have occurred on the silt in the samples collected. (This process, although frequently called "base exchange" is better termed "cation exchange" (Rakestraw, 1949).) The extent of cation exchange required to account for the observed results is not unreasonable. A simple calculation indicates its magnitude. One of the observed Ca/Na points that lies furthest from the calculated curve was found in the Kn-9-2yd. sample. The calculated increase in the Ca/Na ratio at $Cl = 0.369\text{‰}$ is 33.5%; the observed increase is 49.6%. If the concentration of Ca added to the water by cation exchange is $0.16 \times 415 \text{ p.p.m.} \times \frac{0.369}{19} = 1.14 \text{ p.p.m.}$, the observed result may be explained. This value implies that the amount of calcium released by the silt contained in

a litre of water is about $1.14 \times 10^{-6} \times \frac{1000}{0.020} = 0.057$ milliequivalents. Alexander and Johnson (1949, p. 713) and Eitel (1954, p. 492) state that the exchange capacity of montmorillinite is about 1 milliequivalent per gram. Although neither the nature nor the quantity of silt in the present samples was determined, at least 0.1 g. per litre was present in many of the freshest samples. The release of calcium by the clay requires that an equivalent amount of other cations enters the clay structure. The discrepancy between the observed and calculated K/Na values may be accounted for. Not enough potassium is removed, however, to release all the calcium observed. Some magnesium and/or sodium must, therefore, participate in the cation exchange. (Even if all the calcium released resulted from exchange with sodium, the sodium concentration would fall only about 1% and could not be detected by the method used in this study.) Revelle (1941) suggested that magnesium in sea water exchanged more actively than sodium despite its lower concentration.

It appears, therefore, that the differences between the observed and calculated values of the K/Na and Ca/Na ratios may be explained by an ion-exchange process occurring where fresh water containing suspended clay comes in contact with sea water. In their recent study on the uptake of phosphate and other ions by Chesapeake Bay sediments and other materials, Carritt and Goodgal (1954) comment that "the sorptive properties of solid particles suspended in natural waters have been frequently mentioned but seldom measured". Sverdrup *et al.* (1948, p. 990) indicate that "the question of whether or not any exchange takes place when terrigenous clays come in contact with sea water is unsettled". It appears that the results of the present study indicate that such exchange does in fact occur, and that potassium, magnesium and, possibly, sodium participate in the release of calcium from the terrigenous clay. This process presumably contributes to the potassium removal from the ocean discussed by Conway (1945).

If cation exchange between the water and the suspended clay occurs, it is not surprising that the experimental points scatter near the corresponding curves in Fig. 3. The exact value of the ionic ratio depends not only on the extent of dilution, but on the concentration of silt, its nature and possibly on its particle size distribution. (Sverdrup *et al.*, 1946, p. 990). Since the effect of these other factors is not simply dependent on dilution, the values of the K/Na and Ca/Na ratios may also vary irregularly with dilution.

The results that have been described were obtained with water samples from very limited regions fed by rivers with low concentrations of dissolved solids. They suggest possible extension to larger areas of river-diluted water. A river with a higher content of dissolved material should affect the various ionic ratios measurably up to correspondingly higher chlorinities than those reported here.

The effect of the Fraser River on the ionic ratios in the Strait of Georgia may be inferred. From a 1952 report of the British Columbia Research Council the concentrations of Na^+ , K^+ , Ca^{++} , and Cl^- in the Fraser River may be taken as approximately 1, 1, 15 and 1 p.p.m. respectively. Dilution alone is, therefore,

not likely to produce a greater variation in the K/Na ratio in the Strait of Georgia than exists in the inlets studied. The Ca/Na ratio, however, should differ measurably from that of oceanic water up to a chlorinity of 5 to 10‰. The exact magnitude of the variation should depend on cation exchange processes as well as dilution.

SUMMARY

The concentrations of sodium, potassium and calcium have been determined flame photometrically in water samples taken near the heads of two British Columbia inlets. The magnitude of the effect of dilution of sea water by river water on the K/Na and Ca/Na ratios has been calculated and compared with the experimental values. In nearly fresh water samples the Ca/Na ratio is higher and the K/Na ratio lower than simple mixing indicates they should be. Cation exchange of calcium in the river-carried silt by potassium and magnesium (and possibly sodium) is suggested as a possible process that accounts for the observed ionic ratios.

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Spoilage of Fish in the Vessels at Sea:

4. Effect of Removal of Gills on Rate of Spoilage^{1,2}

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ABSTRACT

Removal of the gills from Atlantic cod and haddock definitely retarded the development of off odours and spoilage when the fish were examined as whole gutted fish. It did not make any observable or measurable difference in the quality of fillets cut from these fish.

INTRODUCTION

It has long been a common practice for fishermen on the Canadian East Coast to remove the gills from cod and haddock during the warmer months of the year. This operation is carried out at the time the fish are being gutted and is considered a normal part of dressing the fish on the deck prior to stowage. It is firmly believed by fishermen and by plant operators that removing the gills increases the keeping time of the fish. Many plants make it mandatory that from May 1 to November 1 all cod and haddock shall have their gills removed.

In spite of the fact that this practice is said to be amply vindicated by more than 20 years of practical experience, it seemed worth while to add "gill-removal" to the factors that already have been examined by Castell *et al.* (1956) for their effect on the keeping time of fish stowed in the vessels at sea.

EXPERIMENTAL METHODS

This investigation consisted of comparing gilled and ungilled cod and haddock from shore boats and from deep sea trawlers. The shore-caught fish were gilled at the time of catching, iced in the boats and re-iced in pens at this Station. These were examined and tested periodically for 12 days. In each instance the trawler fish were from the first day's catch. They were gilled (or left ungilled) on the deck, iced down with the remainder of the catch in the hold, and examined shortly after they had been discharged at the wharf.

The comparison of the gilled and ungilled fish consisted of three phases:

1. Examination and grading of the whole gutted fish, with special care in noting the condition of the area of the gills.
2. Uncooked fillets from comparable gilled and ungilled fish were then examined organoleptically for changes in colour, odour and texture.

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²Part 3 of this series appeared in this Journal, 13(2): 207-218, 1956.

3. Trimethylamine values³ (Dyer, 1945, 1950) were determined for each fillet, and pH measurements were taken using a glass electrode.

EXPERIMENTAL RESULTS

SHORE-CAUGHT FISH

DRESSED WHOLE FISH

Judging by the odour and appearance of the gutted fish, it appeared very evident that the removal of the gills retarded spoilage. Between the third and fourth day of storage in ice, the gills became discoloured and began to form slime. At 5 and 6 days they were quite sour and after the seventh day the odour became increasingly offensive. In contrast to this, the fish without gills developed much less odour in the gill region (Table I).

On several occasions a group of experienced fish graders, together with experienced fishermen, pronounced the fish without gills as still marketable, while those with the gills in were condemned as fit only for fish meal.

TABLE I.—Odour of the gill area in gilled and ungilled, dressed shore-caught cod stored in ice.

Days in ice	Gills in	Gills out
1	none	none
2	none	none
4	slightly sour	none
5	sour	slightly sour?
6	sour	slightly sour
7	sour-putrid	slightly sour
10	rotten-putrid	sour
12	rotten-putrid	sour-putrid

FILLETS

Fillets cut from these fish gave an entirely different picture. There was no observable difference in colour, odour, or texture of fillets from corresponding gilled and ungilled fish at any stage during 1 to 12 days' stowage in ice. Table II shows that the average trimethylamine values, as well as the ranges within each

TABLE II.—Trimethylamine values and pH values of fillets cut from gilled and ungilled shore-caught cod stored in ice. Each figure is an average obtained from eight determinations.

Days in ice	Trimethylamine values				pH	
	Gills in		Gills out		Gills in	Gills out
	Average	Range	Average	Range		
4	0.56	0.36-0.73	0.70	0.36-1.47	6.8	6.9
5	0.77	0.36-1.87	0.74	0.55-1.01	6.7	6.7
6	0.82	0.62-1.14	0.75	0.55-1.09	6.8	6.9
7	0.95	0.52-1.51	0.82	0.42-1.46	6.8	6.8
10	1.78	0.88-2.49	1.98	0.52-4.83	6.9	6.8
12	4.45	1.43-10.60	5.21	2.60-9.09	7.0	7.0

³Trimethylamine value indicates milligrams of trimethylamine nitrogen per 100 grams of flesh.

group, are almost identical for corresponding fillets throughout the stowage period. These results were obtained from the whole fillets. It was just possible that these results, obtained by using the whole fillets, might mask smaller differences in the trimethylamine values of the section adjacent to the gills. Table III shows that using only the portion of the fillets nearest the head, there still was no difference in the trimethylamine values.

TABLE III.—Comparison of the trimethylamine values from the head end of fillets cut from gilled and ungilled shore-caught cod stored in ice. Each figure is an average obtained from three determinations.

Days in ice	Gills in	Gills out
4	0.61	0.61
5	0.95	0.81
6	0.89	0.71
7	1.01	1.08
10	1.44	2.87
12	5.16	4.96

Table IV shows the average trimethylamine values of fillets from gilled and ungilled trawler-caught cod and haddock taken from five separate trips, ranging from 6 to 14 days on ice. These represent both well treated fish that were quite fresh when landed, as well as much older fish that were actually spoiled at the time of discharge from the boat. The difference in the odour and the appearance of the gill area in the gilled and ungilled whole gutted fish was again very evident.

TABLE IV.—Average trimethylamine values for fillets cut from gilled and ungilled trawler-caught fish stowed in ice from 6 to 14 days.

Days in ice	Fish	Average trimethylamine value	
		Gills in	Gills out
6	haddock	0.30	0.34
9	cod	0.96	1.00
12	cod	8.7	7.6
13	cod	10.8	10.6
14	cod	15.6	30.1

Fillets cut from gilled and ungilled fish were examined for colour, odour, texture and taste by a group of graders experienced in judging fresh fish. The almost unanimous verdict was "no discernible difference." Four of these men were asked to examine carefully each individual fillet and attempt to judge whether they were from the gilled or ungilled fish. The results are shown in Table V.

A plant manager with more than 25 years' experience in buying and processing fish was asked to examine some gilled and ungilled fish, using his accustomed criteria of appearance, odour and texture, and to pass judgment on their quality. Without any hesitation, he stated: "We would buy and cut those fish (with gills out) and send the others (with gills in) to the fish meal plant."

Five minutes later the same plant manager was unable to distinguish between the fillets cut from these same two lots of fish.

Tests were also made with trawler-caught scrod (small, i.e. 1½- to 2½-pound, 0.7- to 1.1-kg.) cod, gilled and ungilled, which were iced down in boxes on the vessel for 7 days. The fillets cut from these fish were all spoiling. There was no obvious difference in the odour or appearance of the fillets in the gilled and ungilled fish. The average trimethylamine values were: gilled, 3.37; ungilled, 3.07.

TABLE V.—Guesses by four experienced graders as to whether the fillets they examined were cut from gilled or ungilled fish from an otherwise similar lot of cod held 12 days in ice.

Fish No.	Trimethylamine value	Gills actually:	Guesses by four graders			
			A	B	C	D
1	7.6	In	In	Out	In	Out
2	10.7	In	Out	Out	In	Out
3	11.8	In	Out	Out	In	Out
4	7.8	In	In	In	In	In
5	5.7	In	Out	Out	Out	In
6	6.8	Out	Out	Out	In	In
7	7.4	Out	In	In	In	In
8	7.8	Out	Out	Out	Out	Out
9	6.4	Out	Out	Out	In	In
10	10.4	Out	In	Out	Out	Out
11	6.9	Out	Out	Out	Out	Out

SPOILAGE OF THE GILL TISSUE

When it was found from repeated tests that the presence of decomposing gill tissue had no effect on the appearance or the trimethylamine values of the fillets from adjacent portions of the flesh, a number of tests were made on the gills themselves. It was found that as the gills spoiled, their trimethylamine content increased. The following series of determinations are typical of what was found:

Trimethylamine values	
Gills	Fillet
2.3	0.32
7.9	0.56
14.8	1.78

The diffusion of spoilage products from the gills into the flesh from which the fillets were cut was therefore apparently very much less than the diffusion of these products from the spoiling surfaces of the fish or the gut cavity into the muscle immediately beneath (Wood, Sigurdsson and Dyer, 1942; Dyer, Dyer and Snow, 1946). This is not unexpected when one considers the differences in the spatial relationships of the gills and skin or gut surfaces to the fillet muscle. Not only are the gills more remote, but they are not in direct contact with the flesh to be filleted, as in the case of the skin and the peritoneal lining.

A somewhat similar observation was made by Proctor, Nickerson and Goldblith (1950) who found that the trimethylamine and the volatile acids which were produced in the intestinal content of ungutted haddock do not diffuse into the flesh as long as the intestines remain intact.

DISCUSSION

The results of these experiments indicate that when fish are to be filleted there is little or nothing to be gained by the common practice of removing the gills at the time they are being eviscerated. This is directly contrary to the opinions of those in the trade who have had long experience in handling and processing fresh fish. It is interesting to surmise how this paradox has developed.

Almost four decades ago Gross (1919) observed that many fish dealers believed that eviscerated fish in which the gills have not been taken out putrefy more rapidly than those in which the gills are removed. To verify this, Gross himself exposed gilled and ungilled fish in a warm room and found a strongly putrefactive odour developing from the spoiling gills. He also showed that gill tissue was a good medium for the development of certain bacteria isolated from the fish. *But he did not compare the edible muscle from the gilled and ungilled fish.* Those were the days before filleting had become an extensive practice; fish generally were sold in the round or as dressed fish. In that case it would be a distinct disadvantage to have offensive-smelling, putrid gill tissue attached to the fish when it appeared on the market. The reaction would be the same as that of the graders in the present experiments, where they condemned the gutted fish as unfit for food because of the putrid condition of the gills. It was not until after this practice of removing the gills became firmly established that the marketing trend from whole fish to fillets took place. However, once it did become fixed in the minds of the fishermen, the practice was automatically carried over into the period when these fish were chiefly marketed as fillets, and it was no longer necessary to remove the gills.

There are available at the present time a considerable number of bulletins and papers dealing wholly or in part with the practical aspects of handling fish in the boats and vessels at sea. Among these are the following: The Care of the Trawlers' Fish (Reay and Shewan, 1949); The Spoilage of Fresh Fish and its Control (Reay, 1949); The Preservation of Whitefish at Sea (Reay, 1951); Chilling and Freezing Preservation of Fish on the Fishing Vessel (Reay, 1952); Care of Trawlers' Fish (Cutting *et al.*, 1953); The Quality of Fish: Can it be Improved? (Cutting, 1954); Improved Quality and Packing of Fresh Fish as a Means of Stimulating Consumption (Gerhardsen, 1954); Preservation of Trawled Stockfish (Dreosti, 1949); The Preservation of Fish by Chilling (Dreosti, 1951); Chemistry and Advance in Fish Processing (Lovern, 1952); Recent Progress in the Handling, Stowage and Transport of Whitefish (Shewan, 1951); Fish Processing Handbook for the Philippines (Avery, 1950); The Preservation of "Wet" Fish (Riemann and Bramsnaes, 1950). Not in any of these papers do the authors suggest or recommend that gills be removed as a means of preserving the quality of the fish. Furthermore, a review of government regulations for handling fish in most of the important fishing countries of the world has shown that gills are rarely if ever mentioned. In contrast to this, almost all literature dealing with the organoleptic criteria for judging the quality of fresh and spoiling fish suggest that the condition of the gills is one of the most important factors to consider. This, of course, would presuppose that the gills have not been removed.

Occasional exceptions have been encountered to this absence of specific instructions regarding the removal of gills. In Norwegian regulations of May 19, 1950, where treatment of tuna is being defined, it is stated that the gills must be removed. And in a United States Fish and Wildlife Fishery Product Report (No. 9, May, 1953), in discussing the handling of troll salmon, it is advised that "all parts of the entrails that carry the stomach acids should be removed, as well as the gills."

If the removal of gills is as important as some of our Canadian fishermen consider it to be, why have the leading authorities of the world in fish technology apparently neglected to take it into consideration? The results of these experiments would indicate that although gill removal definitely improved the odour and appearance of these gutted fish, there are grave doubts as to whether gill removal adds anything to the quality of the edible muscle within the fish.

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On the Sharpness of Oceanographic Boundaries South of Nova Scotia^{1,2}

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ABSTRACT

The waters south of Nova Scotia are characterized by extremely sharp boundaries both in the horizontal and vertical planes. Temperature changes of the order of 3 Centigrade degrees per metre depth and of 1.5 Centigrade degrees in 100 metres' travel have been observed. Such boundaries must constitute significant barriers to the migration of marine life forms.

OCEANOGRAPHIC conditions in the waters lying off the southern part of Canada's Atlantic Coast are marked by the existence of extremely sharp boundaries across which temperature and salinity change abruptly. Hachey (1942) described the waters on the Scotian Shelf and called attention to the stratification into three distinct horizontal layers. His data show changes in temperature as great as 12 Centigrade degrees in 15 metres at the summer transition from surface to intermediate layers. Recent widespread use of the bathythermograph has shown that this thermocline may have gradients as great as 3 Centigrade degrees per metre. Figure 1 shows reproductions of bathythermograph traces from a survey in August, 1952. Figure 1A shows an observation from the eastern portion of the Scotian Shelf (Lat. 45°18'N., Long. 60°19'W.) where temperature changed 10.5 Centigrade degrees in 3 metres, from 20.0°C. at the 17-metre level to 9.5°C. at the 20-metre level. An observation in the Gulf of St. Lawrence (Lat. 48°02'N., Long. 63°24'W.) showed (Fig. 1B) a change of 12.9 Centigrade degrees in 4 metres from 16.4°C. at the 16-metre level to 3.5°C. at the 20-metre level.

Marked vertical boundaries also exist, the most notable being the "slope water boundary" between "coastal" and "slope" waters, and the abrupt boundary associated with the northern edge of the Gulf Stream. The slope water boundary has been discussed by McLellan, Lauzier and Bailey (1953) who presented some data on its geographical variations. Their temperature sections show that an increase of 10 Centigrade degrees in 10 miles at the 100-metre level is not uncommon when crossing the boundary.

Figure 2 shows the vertical temperature distribution in a line running south from the western edge of the Grand Banks. This section, occupied in June 1952, shows the two boundaries to be particularly well defined. During this survey a salinity-temperature-depth recorder (Jacobsen, 1948) was in operation with its sensing element towed at the surface. The temperature and salinity records

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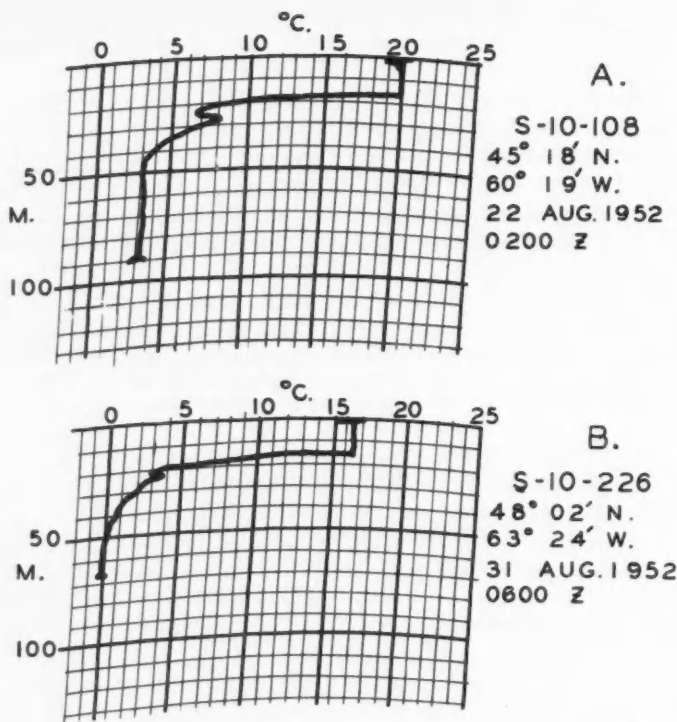


FIG. 1.—Bathythermograph traces from the Scotian Shelf (A) and the Gulf of St. Lawrence (B).

obtained on crossing the slope water boundary and the northern edge of the Gulf Stream are reproduced in Figs. 3A and 3B respectively. In a distance of 3 nautical miles at the slope water boundary, temperature rose from 13.6°C. to 18.3°C., and salinity from 32.8‰ to 34.2‰. At the Gulf Stream edge, temperature went from 19.8°C. to 22.8°C., and salinity from 34.7‰ to 36.6‰, in less than one nautical mile. At one of these boundaries Smith (1931, fig. 122) observed a change in surface temperature of approximately 12 Centigrade degrees in a ship's length (125 feet, 37.5 metres).

Figure 4 shows three successive bathythermograph traces from LaHave cruise 6 in March 1954. This survey line, running in from the slope water area on a course of 325° true, found a shallow surface layer (less than 40 metres) of cold coastal water pushing out over the warmer slope water for some 25 nautical miles. This cold layer is shown in observation 162 but not in observation 160 which was entirely within the slope water. The ship was stopped for each observation and the bathythermograph was not lowered until the ship had lost most of its way. It is probable that a residual velocity as great as 2 knots would be maintained and that, during the 5 minutes while the bathythermograph was in the water, the ship may have travelled 0.17 nautical mile (345 yards or 0.31 kilo-

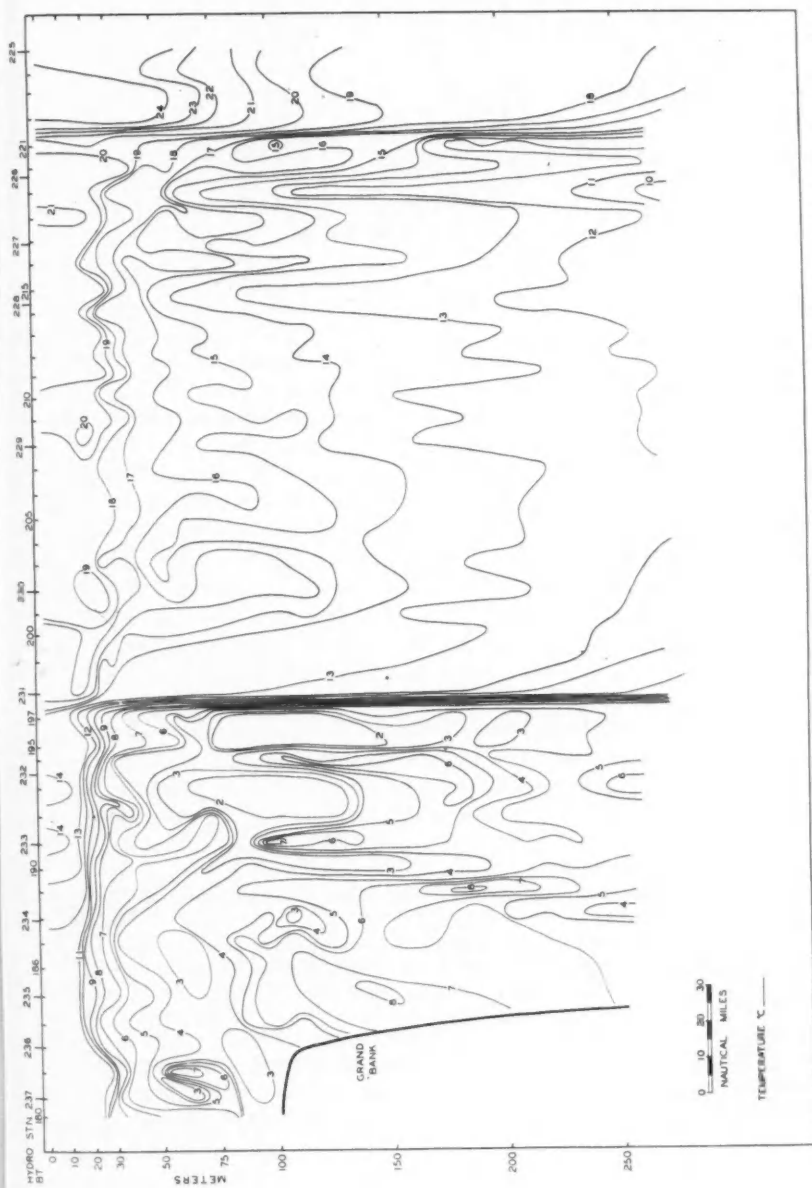


FIG. 2.—Vertical temperature distribution from Lat. $44^{\circ}25'N.$, Long. $52^{\circ}30'W.$ to Lat. $39^{\circ}32'N.$, Long. $51^{\circ}54'W.$ on 25 and 27 June 1952.

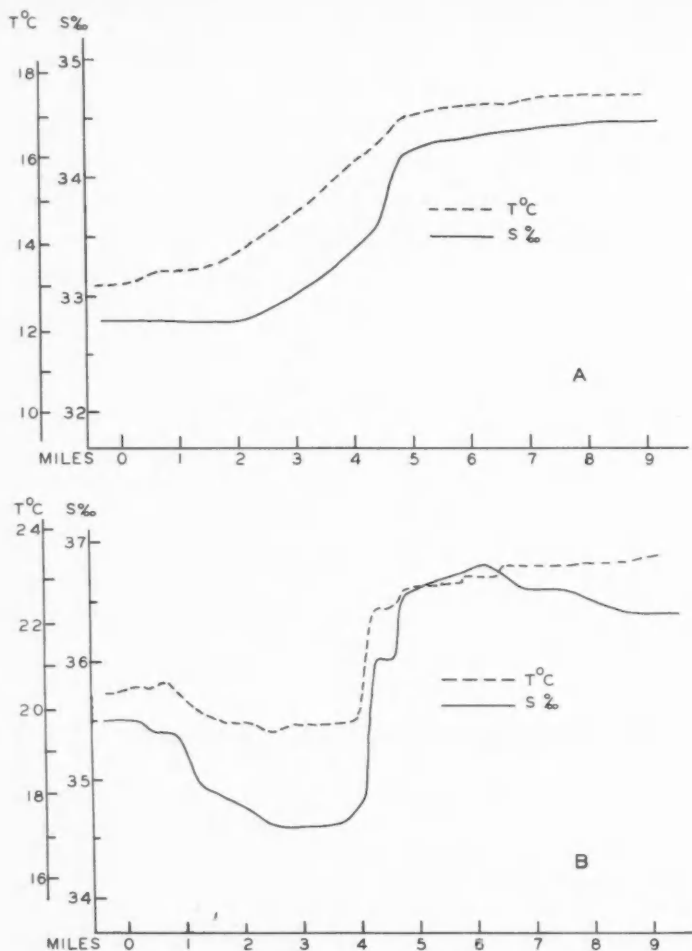


FIG. 3.—Variations in surface temperature and salinity observed when crossing the slope water boundary (A) and the Gulf Stream edge (B) on 26 and 27 June 1952.

metre). The double trace at the surface in observation 161 indicates that the bathythermograph was lowered in slope water (surface temperature $14.1^{\circ}\text{C}.$) and, before it was brought to the surface, the ship had drifted into the tongue of cold surface water (surface temperature $9.3^{\circ}\text{C}.$). The surface boundary at this point must have displayed a horizontal temperature gradient in excess of 1.5 Centigrade degrees per 100 metres.

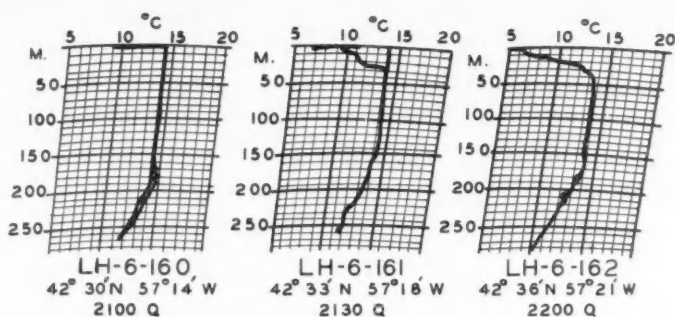


FIG. 4.—Three consecutive bathythermograph traces from LaHave cruise 6, 9 March 1954.

While these examples of the abruptness of thermal boundaries tend to be slightly more extreme than are average conditions, they are indicative of the nature of conditions which generally pertain. Steep gradients of temperature and salinity, both horizontal and vertical, are characteristic features of the waters off Canada's southern Atlantic Coast. In a very real sense these boundaries must act as physical barriers to marine life. It would be expected that many planktonic forms would thrive on one side of the boundary and be unable to exist on the other. The behaviour patterns of the larger nektonic forms would be significantly altered if they indeed did cross such a boundary. Marked vertical gradients are, of course, a regular feature of coastal waters in the Temperate and Polar Regions, especially where the fresh water run-off makes a large contribution to the formation of a stable surface layer. Vertical boundaries are also common wherever major ocean currents transport a water mass out of its region of formation. It is only with the recent advances in observing techniques that it can be appreciated how strong the existing gradients may be. In many parts of the world, the effect of such boundaries in concentrating fish is being exploited with important economic results.

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On the Origin of Deep Baffin Bay Water¹

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ABSTRACT

A comparison of the temperature-salinity relationships of waters found in the Arctic Ocean, Baffin Bay and Smith Sound shows that the deep Baffin Bay water originates in the Arctic Ocean rather than through an influx of a mixture of Labrador Sea deep water and Baffin Bay surface water, the salinity of which has been increased sufficiently by freezing to cause the water to sink, as suggested previously by other investigators.

INTRODUCTION

In the analysis of the oceanographic data collected during the 1954 cruise of H.M.C.S. *Labrador* to the Canadian Arctic (Bailey, 1955), it was noted that there were certain marked relationships between the temperature and salinity characteristics of the waters in the Arctic Ocean, Smith Sound and Baffin Bay. These relationships suggest that the water found at depths greater than 1250 metres in Baffin Bay originates in the Arctic Ocean.

The deep Baffin Bay water, according to Sverdrup, Johnson and Fleming (1942, p. 664), represents a mixture of Labrador Sea deep water with Baffin Bay surface water, the salinity of which has been increased sufficiently by freezing to cause the water to sink.

It will be shown that an Arctic Ocean origin is the simpler explanation of the characteristics of these waters.

GENERAL CIRCULATION AND PHYSIOGRAPHY

The interchange of waters between the Atlantic and Arctic Oceans takes place principally between Greenland and Scotland. The main inflow is across the Wyville Thompson Ridge between the Orkneys and Iceland, while the main outflow takes place through Denmark Strait, between Iceland and Greenland (Sverdrup *et al.*, 1942, p. 660). An additional outflow from the Arctic Ocean occurs through the Canadian Archipelago into Baffin Bay and thence into the Atlantic (Kiilerich, 1939).

Recent charts show that Baffin Bay is a basin with depths greater than 2100 metres in the central portion. In the north, it is in communication with the Arctic Ocean through Smith, Jones and Lancaster Sounds. Communication with the Arctic Ocean is limited by sills in these sounds to depths of 200, 175 and 180 metres, respectively. In the south, there is communication with the Atlantic

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Ocean through the relatively wide Davis Strait which has a sill depth of 700 metres.

In Baffin Bay, the general circulation is dominated by the extension of the West Greenland Current northward across Davis Strait Ridge, and the Baffin Land Current which flows southward along the east coast of Baffin Island. The West Greenland Current is a warm current, but it rapidly loses heat as it flows northward (Sverdrup *et al.*, 1942, p. 665). The Baffin Land Current, which according to Smith, Soule and Mosby (1937) makes up two-fifths of the waters found in the Labrador Current, is composed mainly of the outflow of Arctic Ocean waters through Lancaster Sound, and the recurved and cooled remnants of the northward extension of the West Greenland Current. An additional supply of Arctic water is provided by the flow through Jones and Smith Sounds (Kiilerich, 1939; Bailey, 1955).

WATER MASSES

During the summer the water column in central Baffin Bay has been shown by Riis-Carstensen (1936) to be comprised of four masses of water, viz:

1. Surface water exhibiting temperatures between -1.0° and 3.5°C . with corresponding salinities between 30.0 and 32.7‰. This water is largely influenced by solar warming and the melting of ice.
2. Cold water, sometimes described as Polar or Arctic water because of its frigid temperature. Temperatures are less than -1.0°C ., with a minimum of -1.8°C . A salinity of 33.7‰ is associated with the minimum temperatures.
3. Warm water. The warm water found in Baffin Bay is a mixture of "Labrador Sea intermediate" water and the cold water described above. Temperatures in the warm water layer are generally between 1.0° and 1.4°C ., with a salinity of about 34.4‰.
4. Deep water found at depths between 1250 and 2100 metres has a temperature of -0.5°C . and a salinity of 34.45‰.

In the Arctic Ocean during the summer months, the water column has been described by Sverdrup *et al.* (1942, p. 658) as composed of four water masses, viz:

1. Surface water exhibiting a wide range of low temperatures and very low salinities (-1.0 to 2.2°C ., and 4.2 to 27.5‰). The surface water in the Arctic Ocean is largely governed by ice conditions. In general, the greater the concentration of ice, the lower the temperatures and salinities.
2. Cold water having temperatures lower than -1.0° and as low as -1.8°C . with salinities ranging between 32.4 and 33.4‰.
3. Warm water. The warm water found in the Arctic is formed by Atlantic water from the Norwegian Sea which has mixed with waters from the "cold water" layer. A maximum temperature of 0.5°C . occurs at about 500 metres with a corresponding salinity of 34.8‰.
4. Deep water. The deep water in the Arctic is formed in the Norwegian Sea. Characteristic temperature and salinity are -0.85°C . and 34.9‰, respectively.

DATA USED

The oceanographic stations used in the presentation of this report are given in the accompanying table, and their locations are shown in Fig. 1.

Oceanographic stations

Station	Lat. N.	Long. W.	Date	Reference
Godthaab 23	62° 07'	57° 48'	13 June 1928	(Riis-Carstensen, 1936)
" 59	72° 26'	62° 44'	18 July 1928	
" 98	78° 16'	73° 41'	8 Aug. 1928	
Labrador 23	78° 21'	74° 16'	12 Aug. 1954	(Bailey, 1955)
" 92	70° 55'	137° 52'	12 Sept. 1954	

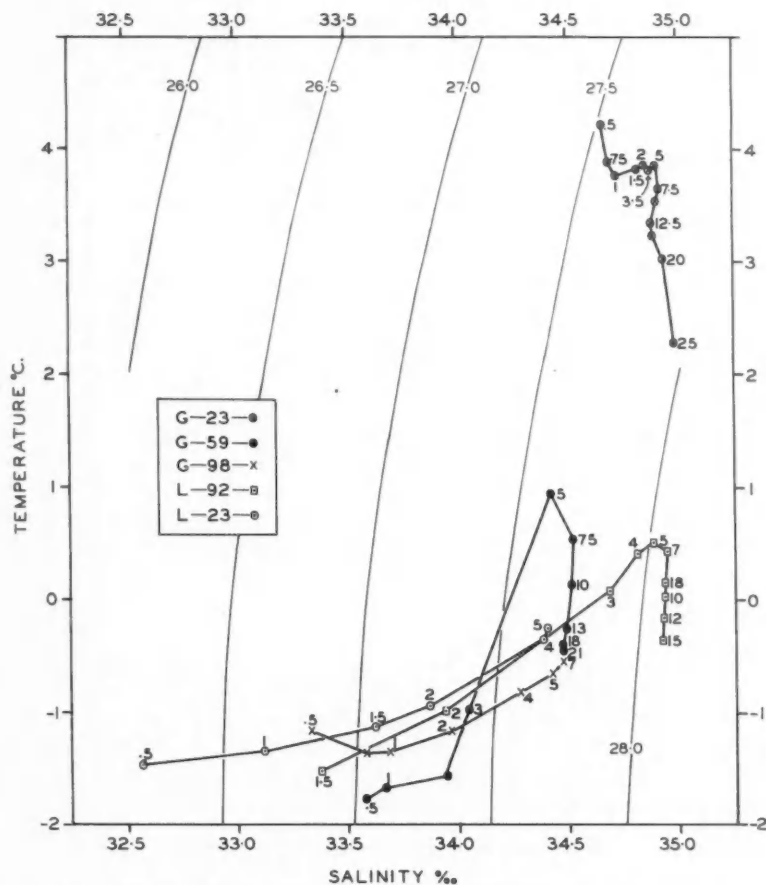


FIG. 2.—Temperature-salinity curves for selected stations located in the Canadian Arctic. The depths of observations are indicated in hectometres.

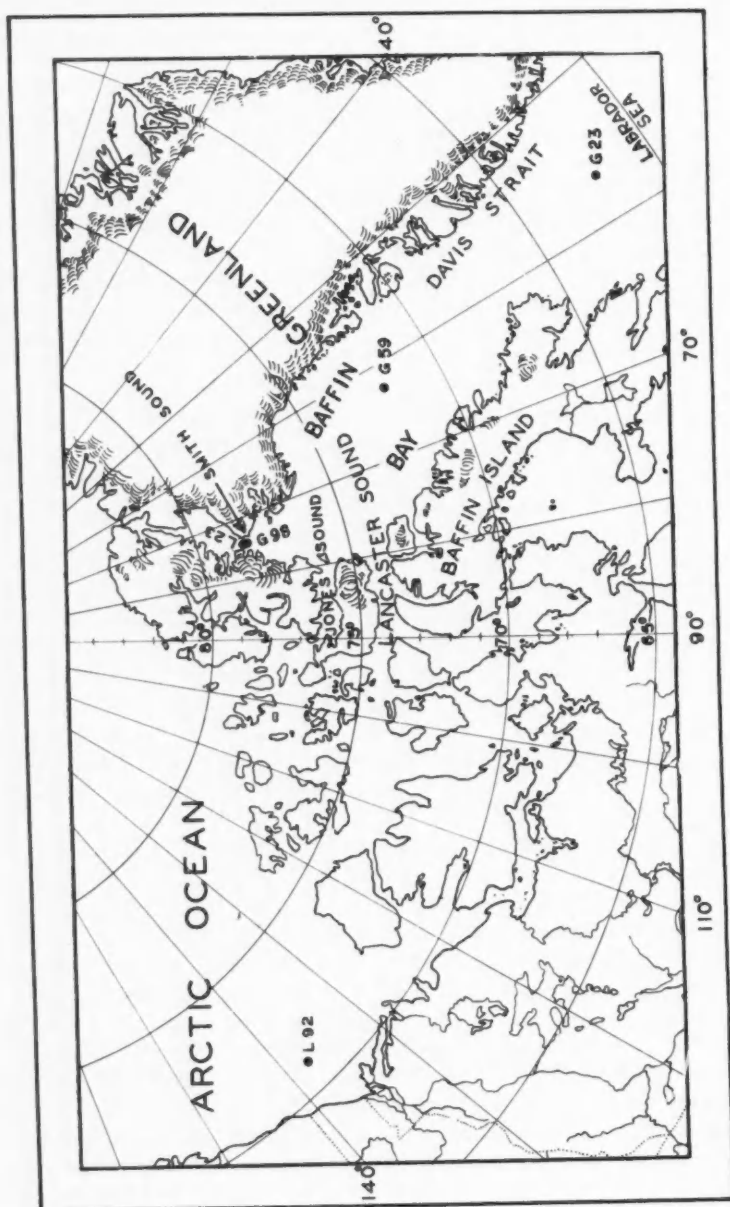


Fig. 1.—Map of Canadian Arctic showing the location of oceanographic stations.

T-S DIAGRAMS

Figure 2 shows five T-S curves for the waters at 50 metres and below in Baffin Bay (G59), Smith Sound (L23, G98), the Arctic Ocean (L92), and the Labrador Sea (G23). The numbers near the top of each curve represent the depths of the observations in hectometres.

The T-S curve for station G59 shows that the waters in Baffin Bay are made up of the cold water layer, the warm water layer and the deep water, with mixtures between the adjacent layers. Station L92 in the Arctic Ocean shows a similar structure but with distinctly different characteristics typical of the various layers. The T-S curves for stations L23 and G98 in Smith Sound belong to the Arctic type.

The bottom waters in Smith Sound display the same T-S characteristics as waters found in the Arctic Ocean at a depth of about 250 metres and both are similar to deep Baffin Bay water.

It therefore may be concluded that the deep Baffin Bay water found at depths between 1250 and 2100 metres originated in the Arctic Ocean at depths of about 250 metres.

DISCUSSION

The replacement of the deep Baffin Bay water may take place either as a very slow and continuous process or as a surge of heavy water through Smith Sound. Waters found at depths greater than 250 metres in the Arctic Ocean are heavier than any waters found in Baffin Bay (see Fig. 2). Since the sill depth in the "Smith Sound channel" to the Arctic Ocean is about 200 metres, it may be expected that a flow of heavy Arctic water may take place at relatively frequent intervals. This is borne out by the fact that the dissolved oxygen content in the deep Baffin Bay water in both 1928 and 1953 displayed the same low value (3.53 ml./l.). Assuming that the replacement of the deep water is not continuous and that the rate of decrease in the dissolved oxygen content is constant, it may be concluded that the observations of 1928 and 1953 were both taken at about the same length of time after a replacement had occurred, and that this period was no longer than 25 years.

Further, from the T-S curve from the Labrador Sea (G23), it is clearly evident that the deep Baffin Bay water did not originate in that area. In addition T-S curves produced from late winter observations in Baffin Bay lack only the superficially warmed surface layer as compared with T-S curves produced from mid-summer observations. This fact, coupled with the slope of T-S curve G59 between 200 and 500 metres, shows that the deep Baffin Bay water is not formed by cabelling.

As the question of the origin of the deep Baffin Bay water is examined more fully, it becomes increasingly evident that the explanation of its origin in the Arctic Ocean, its subsequent flowing into the Baffin Bay through Smith Sound, and its sinking to the bottom, is a most plausible one.

ACKNOWLEDGMENT

The criticisms and advice of Mr. H. J. McLellan and Dr. R. W. Trites of the Atlantic Oceanographic Group are gratefully acknowledged.

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The Behaviour of Migrating Pink and Chum Salmon Fry¹

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ABSTRACT

Pink salmon fry which have never schooled are negatively phototactic, prefer a cover of stones and do not emerge into bright light. Those which have schooled show a strong cover reaction when exposed to a rapid increase in light intensity but do not seek cover unless the change is abrupt. In general they remain in bright light after they have schooled. This change in behaviour occurs rapidly (15 minutes or less) when the fry school for the first time. Chum salmon fry establish a definite direction of swimming in the quiet water of a circular channel or basin. The established direction is stable and not permanently disturbed by light or darkness, by water currents, by strong avoiding reactions, by changing the location or by excluding direct skylight. The direction may be initially established in relation to water currents.

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INTRODUCTION

THE downstream movement of juvenile salmon has been described in previous papers as a nocturnal seaward transport of small fish which fail to hold position at low light intensities (Hoar, 1951, 1953, 1954). On the basis of prolonged observations of chum salmon (*Oncorhynchus keta*) and pink salmon (*O. gorbuscha*) maintained in aquaria, tanks and troughs, it was concluded that these species prefer light and show a strong positive rheotaxis. Thus, during the day, they hold position in the exposed areas of the rapidly flowing streams but move seaward in darkness when light intensity falls and rheotactic responses fail.

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Several workers familiar with the behaviour of migrating juvenile salmon under field conditions have pointed out that the postulated mechanism does not agree with observations made during the mass exodus of pinks and chums from the rivers. Neave (1955), in particular, has described an active downstream swimming of pink salmon fry at night and their disappearance at dawn when they are presumed to hide among the stones and gravel. He suggests that a real change both in phototaxis and rheotaxis follows migration and possibly coincides with the commencement of feeding.

The laboratory observations have been repeated many times and the behaviour patterns previously described are certainly those displayed by these fish in aquaria. Moreover, as already emphasized (Hoar, 1954, p. 95), chum salmon behave in the manner postulated when released, during the day, into rivers where they were captured during the previous night. Additional experiments of this type performed in a rocky canal beside Hooknose Creek in 1955 (Fig. 1) showed that pink fry also remained exposed during the daytime and swam actively against the currents. When many thousands of pink salmon (seaward migrants of the previous night) were poured rapidly into a bed of stones, some could later be located by moving the stones but the majority swam out of the stones immediately and moved up and down the canal in schools. When the ends of the canal were screened the fish were also in sight throughout the next day, indicating that they had not sought cover with the gradual increase of morning light. In the pool illustrated in Figure 2, pink and chum fry sometimes schooled back and forth for several days although they had only to migrate downstream over a low waterfall to reach the main river.

It is equally easy to repeat Neave's (1955) careful observations. During the mass exodus of these little fish, thousands of them may be seen at night, by means of a dim light, swimming so rapidly downstream that they create a "bow-wave" (Neave, 1955) in the surface layers. Further, as Neave and others have emphasized, one can usually find only a few pink or chum salmon during the day in streams where tens of thousands are known to be migrating each night. Again, it is not difficult with a shovel to dig them from an old spawning redd and send them scurrying for the cover of nearby stones.

It is evident from these contradictory pictures that something basic must have been missed in the earlier experimental observations or that the techniques used are inadequate to develop a complete picture of the behaviour of these fish. This ethological study of the juvenile *Oncorhynchus* was undertaken on the premise that methods which had been so productive in elucidating the behaviour of several groups of lower animals (Tinbergen, 1951) would lead to valuable results with this important commercial genus of fish. Clearly the matter requires careful re-examination.

Two problems must be considered. The first has to do with possible changes in phototactic and rheotactic behaviour during or following migration. The fish used in earlier studies were often retained for many weeks and changes in behaviour may have occurred during this period. Thus, the behaviour described may not always have been that of migrating salmon. Detailed comparative.



FIGURE 1.—Estuary of Hooknose Creek just below the counting fence. The experimental side channel shown at the right can be screened at three points. Fry releases were made in the upstream area (lower part of photograph).

FIGURE 2.—Small tributary of Hooknose Creek showing pools where fry releases were made; Hooknose Creek at top of photograph.

measurements of the behaviour of actively migrating fry should yield data pertinent to this question.

The second problem raises a distinctly different type of question: viz. whether salmon can learn and maintain fixed directions of swimming over long distances in spite of changing conditions of light, current and the variety of variables which must be encountered in rivers, lakes and oceans. It is now known that some animals, for example bees (von Frisch, 1950), starlings and pigeons (Kramer, 1952, 1953), beach fleas, *Talitrus* (Pardi and Papi, 1953), and spiders (Papi, 1955) can navigate, sometimes for long distances, using the sun—also the moon for *Talitrus* (Papi and Pardi, 1953)—to guide their course. Fixed directions of orientation by fishes, however, seem not to have been demonstrated under controlled conditions although it is frequently urged that this must occur in nature.

The experiments reported here were carried out at the Port John Field Station of the Fisheries Research Board of Canada during the period of pink and chum fry migration in 1955. All fish used were actively migrating. They were obtained from a counting trap or weir and introduced into the different pieces of apparatus during the same day. New lots were captured for each experiment. The fish were not fed during the observations. A total of 907,458 pink fry and 353,761 chum fry passed through the traps in Hooknose Creek in 1955 and the experiments were carried out during the period of most active migration. A sample of 20 pink fry measured 35.1 mm. average fork length (standard deviation, 1.3) and the same number of chums averaged 37.9 mm. ($s = 2.2$).

RELATION OF PINK SALMON FRY TO RIVER BOTTOMS

The galvanized iron trough used in these experiments was 360 cm. long, 30 cm. wide and 20 cm. deep. The interior was coated with black asphalt varnish and contained two areas of gravel mixed with stones (10 to 13 cm. deep) as shown in Figure 3. These two areas thus divided the trough into three pools and two gravel beds. The trough was located out-of-doors. Approximately 40 litres per minute of river water poured from a pipe 5 cm. in diameter into the trough over the upstream end of gravel bed A (Fig. 3) and flowed away through a screen at the other end to maintain a water depth of 14 cm.

FRY RELEASED DURING THE DAY

Pink fry used in these experiments were obtained from the pens of the counting weir during the morning and had moved downstream into the pens during the previous night. Samples of 100 were counted into 10-litre glass bottles and exposed either to diffuse daylight (light-adapted fry) or placed in total darkness (dark-adapted fry). In both cases, the temperature was maintained at that of the flowing river water. After a period of about 4 hours fry were poured as rapidly as possible from these bottles into gravel A or pool II (Fig. 3). After 2.5 to 5 hours all fry which could be netted without

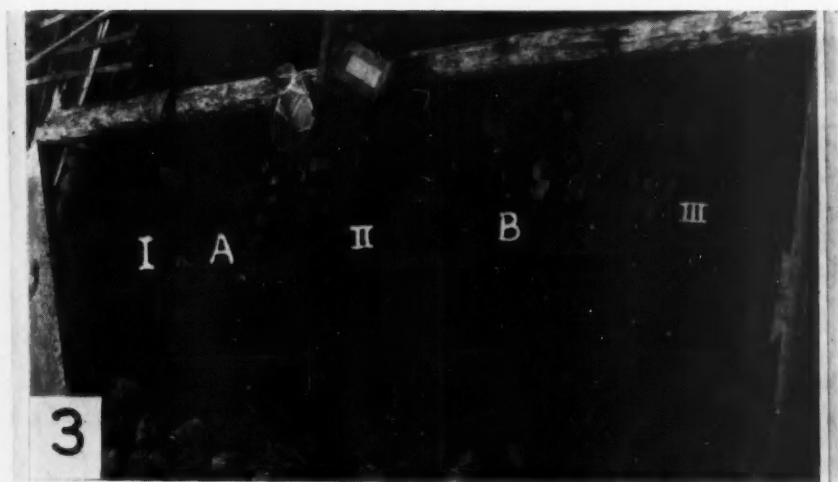


FIGURE 3.—Trough in which pink salmon fry were released; I II and III are three pools separated by two areas of stone and gravel, A and B; inflow of river water at left; outflow at right.

FIGURE 5.—Section of counting weir showing screen onto which pink fry are carried by water flowing over a dam (upper right of photograph) and washed into the trough below (lower left of photograph). Debris and small fish are evident on the screen.

disturbing the stones were removed. Several checks were made during the course of the next hour to establish the fact that all fry which were not remaining "permanently" in the gravel had appeared and been captured. Since fry school compactly, it was not difficult to net all the exposed animals from the pools at either end of the trough.

The reactions of the light- and dark-adapted fish are markedly different. When poured into gravel A the dark-adapted fish disappear instantly and almost entirely. A few appear in the pools within the next few minutes but the majority are not evident even after 3 to 6 hours. The light-adapted fish, on the other hand, when treated in the same way rise immediately into the surface layers of water and dart away from the experimenter. They school promptly and collect in one or other of the pools or migrate back and forth. When startled, either immediately following release or during the subsequent hours of observation, they swim in schools *over the rocky areas* and do not take shelter under the rocks unless the disturbance is violent and the school broken up into small units.

The reaction of the light-adapted fish poured into pool II is the same as that of the fish just described. The dark-adapted fish, however, sink at once onto the bottom of the trough. Some scatter from this point into the nearby stones but many hold their position at the bottom of the pool for a few seconds and then begin to rise and school together. Within a minute or less they are swimming in schools over the rocks into other pools, behaving essentially the same as the light-adapted fish. It is thus evident that unless the change in light intensity is abrupt and cover is readily available, the schooling reaction rather than the cover response is the normal behaviour of these pink salmon during the day.

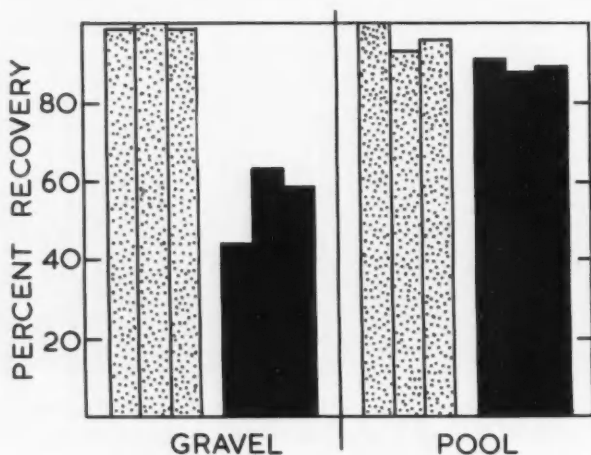


FIGURE 4.—Percent pink fry captured from trough after being released into gravel A or pool II. Stippled bars, light adapted fish; solid bars, dark adapted fish.

Quantitative data are shown in Figure 4. After from 2 to 6 hours, whether dark- or light-adapted, more than half of the fish were exposed in the pools and readily captured. In the experiments described in the next section it was shown that as many as 135 pink fry sometimes remained hidden and were never seen during the daylight in these same areas of rock. Thus adequate cover was available if the fish had reacted to it and these experiments provide, at best, a partial and unsatisfactory explanation for the disappearance of pink fry observed in streams at daybreak.

FRY RELEASED DURING THE NIGHT

These fry were collected at midnight from the screens of the counting fence (Fig. 5). They were removed individually into a tobacco can and then transferred in lots of about 10 fish to a covered pail of water. Groups of 100 fish were in this way collected for these experiments. Although the fish were obtained from the screens with the aid of light, they had come onto the screens in darkness and had presumably never experienced the schooling reaction. It was impossible to avoid some light in collecting and transferring them to the bucket but their schooling experience must have been brief or non-existent. Fish collected in this manner were (a) poured into gravel A in "total" darkness (unschooled fish) or (b) exposed in a large bucket under a 200-watt electric light for about 15 minutes and then poured into gravel A in "total" darkness (schooled fish). In each case the experiment was then left undisturbed until 9 a.m. when the pools were fished as previously described.

It is apparent from Figure 6 that unschooled fish took cover in greater numbers than schooled fish (about 25% greater). Since the method of collecting and handling the fish cannot have excluded all experience in light, it is clearly indicated that brief schooling experience brings about a permanent change in the behaviour of pink fry. This phenomenon—evidently some very rapid type of

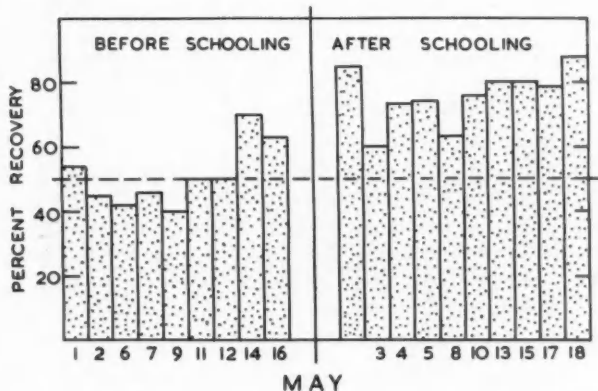


FIGURE 6.—Percentage of released fish recovered from trough, further description in text.

learning—seems to result in a forsaking of the protection of the gravel for the protection of the school. Thus it would appear that if pink fry move as individuals during the night they will, as individuals, take cover again at dawn. Several experiments with chum fry indicated that their reactions were essentially the same. These findings support Neave's (1955) observations.

Figure 6 suggests further that, as the season of fry migration comes to a close, there is a decreased tendency for unschooled pink fry to take cover at dawn. Recoveries, which during the early part of May were of the order of 45%, rose to 65% and 70% about the middle of May when the migration was coming to an end. Since the technique of capturing and handling the fish in darkness probably improved during this period, the results indicate that either the fish caught had schooling experience prior to trapping or were showing a greater tendency to emerge from the gravel. It was possible to examine this matter in another way. A number of fish (varying from 15 on one occasion to 135 on another) were known to be somewhere hidden in the stones when the trough was fished for the last time about 8 p.m. in the evening. Many of these emerged after dark and were captured with the aid of a lantern at midnight before adding more fish. Observations showed that few fish emerged after this midnight fishing. Results of the midnight fishing experiments (Fig. 7) show that after May 13 the percentage of the fish known to be present which emerged after darkness rose to almost 90% at the end of the experiment when the 1955 migration of pink fry was rapidly nearing an end.

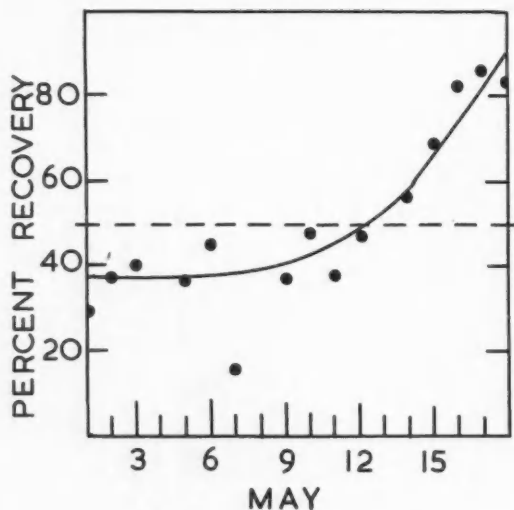


FIGURE 7.—Percentage of fish emerging from gravel in experimental trough between 8 p.m. and midnight.

ODOURS IN SPAWNING REDD GRAVEL

In view of the remarkable olfactory acuity of fish (Hasler, 1954) it seemed possible that odours in salmon spawning redds (decaying eggs, egg cases and dead alevins) might serve as an additional factor in attracting fish to the gravel at daybreak and in holding them there. Experiments carried out prior to May 5 were performed with gravel dug from a pink salmon redd and containing dead eggs, fungused alevins and empty egg cases. On May 4 the trough was emptied, washed thoroughly and arranged with rain-washed and sun-dried gravel and stones. Figure 6 does not lend any support to the idea that fry may be held in the spawning redd by the specific odours there. Percentages were of the same order before and immediately after May 5.

CONSTANT DIRECTIONS OF SWIMMING FOR LONG DISTANCES

The word "migration" implies a movement from one place of residence to another and, as far as fish are concerned, it usually connotes that these journeys are cyclical or periodic in nature and that the direction of travel is maintained over long distances in spite of diurnal and moderate variation in meteorological and hydrological conditions. The essential feature is an active movement of animals in definite direction, over considerable distances, through a variety of changing conditions. In previous papers emphasis has been placed on the dynamics of the environment as directing and controlling the downstream migration of pink and chum salmon fry (Hoar, 1953). It has now been possible to show that chum salmon fry in quiet water may swim for prolonged periods in a constant direction. This experimental demonstration of an ability to maintain a direction emphasizes the dynamics of the fish divorced from obvious guiding factors such as rheotaxis.

The behaviour discussed in this section was previously observed, depicted and quantitatively described as "roaming in quiet water" (Hoar, 1954, pp. 77-78). Its significance, however, was not appreciated because the apparatus used required an abrupt turning of the fish which frequently resulted in milling and obscured definite directions which might otherwise have been noted. The present experiments, made in circular channels, permitted indefinite travel in a clockwise or counter-clockwise direction.

APPARATUS

Two sizes of circular channels were used (Fig. 8). The larger channels (experimental series LC) are 20 cm. wide and 20 cm. deep with an outside diameter of 120 cm. Thus the circumference at the center of the channel is 314 cm. The channels were placed in a pool where flowing water maintained the temperature close to that of the nearby river. Four equally spaced 2.5-cm.-diameter holes in the center bottom of the channels controlled the water level (15 cm.) at that of the pool. Water (8 to 9 litres./min.) could be circulated from 13-mm. diameter rubber tubes to establish clockwise or counter-clockwise currents in the channels. The tubes could be removed (Fig. 8) without startling

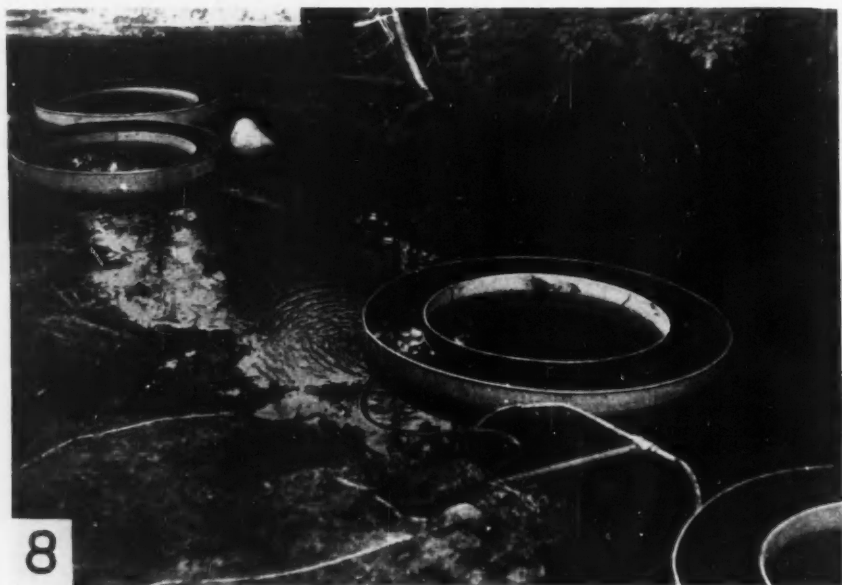


FIGURE 8.—Circular channels. Series LC, lower right area of photograph; series SC, upper left area of photograph; hoses used to create currents are evident between the two larger channels.

the fish while they swam on the far side of the channels. Since chum fry swim up from the bottom they did not escape through the holes. Schools of 20 fry were used and all experiments performed under outdoor conditions.

The smaller channels (experimental series SC) are 10 cm. wide and 15 cm. deep with an outside diameter of 90 cm. The circumferential distance at the center of the channel is 251 cm. Ten fry were used in these channels and the water level was maintained at about 10 cm. They were kept under conditions similar to those applying in the larger channels (Fig. 8). These smaller channels were of such a size that water could readily be poured from them into pails or they could be carried from one locality to another.

Observations were also made with schools of 40 chums in a large circular basin 120 cm. in diameter and 30 cm. deep (experimental series B). It too was placed in a pool and the depth of water maintained at about 20 cm. by two equally spaced 2.5-cm.-diameter holes located 7.5 cm. from the margin.

All pieces of apparatus were constructed of galvanized iron and painted with "Rustoleum" (non-toxic) red paint. Fish were introduced by pouring them from buckets into wire mesh strainers and thence into the apparatus. Thus currents were avoided which would otherwise have developed by adding fish with water. In general observations were made for 10-minute periods at 2-hour intervals from 7 a.m. to 7 p.m.

BEHAVIOUR IN CIRCULAR CHANNELS AND BASINS

In quiet water chum fry quickly establish a clockwise or counter-clockwise direction of swimming. When first placed in the apparatus they school rather compactly and, after the initial fright reaction, swim in one direction or the other. Sometimes the first direction taken becomes the established direction and thus the course is fixed within the first few seconds. In other cases the fish swim first in one direction, then the other, making either complete or partial circuits before turning. In 12 experiments (series LC in quiet water) where behaviour was followed continuously from the beginning the maintained direction was the first direction taken in six cases and was thus fixed within the first minute. In the other six cases the final direction was established within 5 minutes.

Chum fry when undisturbed form rather loose schools. When travelling rapidly in the circular aquaria they may swim in file-like formation along the outer wall so that the group extends around most of the periphery. This was particularly evident in the small channels and the basin. In the large channels single individuals or small groups were frequently left behind by the rapidly moving school. Individuals thus isolated might reverse direction, mill or swim to and fro until caught up by the main wave of the school on its next circuit. Directions were obvious and definite to observers unfamiliar with the background of the work.

It was evident that strong sunshine, heavy shadow, wind in the nearby trees, rain, hail or low flight of birds startled the fish and often interrupted or confused their otherwise orderly travels. Journeys were carefully charted for 141 ten-minute periods of observation, involving 64 different schools of fish in the large circular channels. Uninterrupted circling was recorded in 100 cases. In 41 tests some measure of irregularity occurred: eighteen of these irregularities were recorded in the morning (6 a.m. to 11 a.m.), seventeen in the afternoon (11 a.m. to 4 p.m.) and six in the evening (4 p.m. to 8 p.m.). The more uniform rate of travel observed in the evening may be related to the nocturnal migratory behaviour of the fish and or to the more uniform environmental conditions at that time of day (less wind, absence of strong shadows).

Bright sunshine in particular modifies but does not change the direction. This was most readily observed in the basin where fish were not forced to travel in a definite channel. In bright sunlight the course was angled so that the path became an oval rather than a circle with the length of the oval in line with the sun. The two charts in Figure 9 were based on careful recordings of the migrations of 40 chum fry during 15-minute periods.

The speed of travel varies with the time of day. Mean rate of migration for the 100 ten-minute periods during which travel was continuous and constant was 2.0 complete circuits of the large channel per minute. During the 38 morning periods the rate was 1.8; in the afternoon 1.9 and during the evening 2.4. Thus not only the regularity but the rate of swimming is greatest during the evening.

The movements of these small fish produce no demonstrable pattern of currents which might serve as cues to guide them. Powdered methylene blue was placed on the water surface. In the basin it diffused slowly toward the

bottom at the point of introduction while the fish swam in a wide oval on the opposite side of the basin. The downward diffusion of the dye particles was only disturbed when the fish were driven into it. In the circular channels the fish sometimes continued to swim under the dye and a very slow movement of the surface film in an opposite direction could be noted. The fish, however, circled the apparatus many times while the dye moved only a short distance from the place where it was introduced. Thus, there was no evidence for the production of a pattern of currents which might guide the fish.

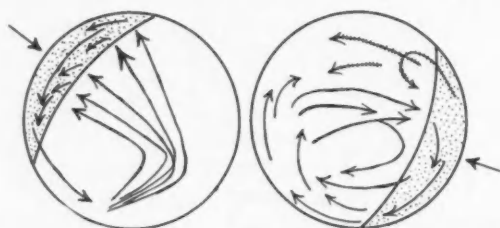


FIGURE 9.—Chart of the course of travel of two experimental groups of chum salmon schools in circular basin. Stippled area; strong shadow; arrows outside circles, direction of sun; arrows inside circle; path of movement by school; crosshatched arrows, "wrong" direction.

DIRECTION RANDOM IN QUIET WATER

Directions are established in a random manner when fish are placed in quiet water. There does not seem to be an innate direction of swimming—such as displayed by man in right or left-handedness. Pertinent data, summarized in Table I, show that the larger number of counter-clockwise journeys recorded is insufficient to establish statistically an increased tendency for movement in this direction. In 11 out of 19 paired experiments where groups were introduced into duplicate identical channels at the same time, one group established a clockwise and the other a counter-clockwise direction of swimming.

TABLE I.—Directions established in quiet water.

Series	Clockwise	Counterclockwise	Chi-square
B	3	3	0
LC	6	9	0.6
SC	10	16	1.385
Total	19	28	1.723

DIRECTIONS BIASED BY INITIAL EXPOSURE TO CURRENT

In the large channels it was possible to create a flow of water in either direction. When the source of water was suddenly interrupted the flow in the channels gradually slowed down and stopped. Fish placed in the channels with flowing water usually showed strong positive rheotaxis, swimming vigorously against the current. Sometimes they held position, but more frequently migrated

against the current, slowly swimming around the channel. Less frequently they drifted in a loose school with the current and occasionally swam rapidly in the same direction and at a considerably greater speed than the flowing water (negative rheotaxis). No attempt was made to establish factors responsible for this variable response. It is recognized that the sign of rheotaxis may change from time to time in chum salmon (Keenleyside and Hoar, 1954). The usual response in these tests was a strong positive one.

Table II shows that an initial exposure to current affects the subsequent direction of swimming in quiet water. Random results are no longer obtained. In 30 out of 40 tests (chi square, 5.000) the established direction was opposite to that of the flowing water. It is probable that the established direction is the one in which the fish are swimming when the current finally ceases although an insufficient number of groups were followed closely enough while the currents were ceasing in the channels to demonstrate this.

TABLE II.—Attempts to establish a predictable direction by initial exposure to flowing water (15–30 minutes). Water speed: 27–30 cm./minute.

Direction of current	Daylight experiments				Midnight experiments			
	Tests	Final direction			Tests	Final direction		
		Same	Opposite	Uncertain		Same	Opposite	Uncertain
Clockwise	13	2	11	0	6	0	6	0
Counterclockwise	15	6	8	1	6	0	5	1
Total	28	8	19	1	12	0	11	1
All tests	40 tests: 8 same direction; 30 opposite; 2 uncertain.							

DIRECTION STABLE FOR PROLONGED PERIODS

A summary of findings (Table III), based on 94 different schools, shows how infrequently (only 5 times) the direction changes over periods of time ranging from 2 hours to 2 or more days. No attempt was made to establish the maximum length of time that chums would swim in one direction. In one case,

TABLE III.—Constancy of direction over prolonged periods. Sizes of schools, LC, 20; SC, 10; B, 40.

Series	Duration	Number of schools	Schools with direction		
			Constant	Altered	Not fixed
LC	hours				
	2–6	35	31	2	2
	7–12	12	8	2	2
	20–24	18	18	0	0
SC	2–10	15	15	0	0
	12–24	6	5	1	0
B	20–24	3	3	0	0
	48–72	5	5	0	0
	Total	94	85	5	4

however, the direction was unaltered and the fish were swimming rapidly after 72 hours.

It is again pointed out that these fish were not observed under controlled laboratory conditions. They must have been frequently stimulated by a variety of factors (changing light, shadows, wind, rain, snow and the activities of men and birds). Under constant conditions, swimming in one direction might even be more regular, or it might quickly cease. This point remains to be tested.

DIRECTION UNALTERED BY A VARIETY OF STIMULI

It is easy to disrupt the journeys of these fish. Nearby movements of the observer will instantly startle and cause the fish to school compactly at one side of the channel or move into shadows. If the alarming stimuli are persistent, the school breaks up and fish are scattered about the channel. When the disturbance is over, however, they quickly school and are usually swimming in the original direction within 2 to 10 minutes. They may circle the apparatus once or several times in a "wrong" direction or move back and forth in one quadrant before the original course is resumed.

By placing a dark cover over one half of the apparatus it is possible to bring circling to an end. This is particularly true during the bright part of the day. Occasionally the fish encircle a half-covered channel apparently undisturbed by the cover but usually they are re-oriented at the boundary between the two areas and emerge infrequently. Their behaviour at the boundary indicates that they are moving to and fro under the cover.

Many other procedures were tried in an attempt to alter the direction of swimming. The data, summarized in Table IV, show a surprising stability of these established directions. It seems evident that some rapid and permanent type of learning must be involved.

Three of the experiments, listed in Table IV, are particularly pertinent to any discussion of this phenomenon. In the first place, it was evident that the type of water current, which when initially applied seemed to govern the direction of migration (Table II), failed to produce a comparable effect after the direction of swimming had been established. In the second place, although direct sunlight may modify the angle of migration, an elimination of direct skylight has no effect on the general direction. The orientation does not seem to depend on the sun or clear sky, unlike fixed directions of movement in some arthropods (von Frisch, 1950; Pardi and Papi 1952; Papi, 1955) and birds (Kramer, 1952, 1953). In the third place, experiments in which schools were moved to other pieces of apparatus or kept for more than 24 hours in distant aquaria suggest that the permanence of the direction must be of a nature that would be highly valuable to fish making long journeys. When fish were kept overnight in aquaria, they were netted from the large channels—a procedure which sometimes involved considerable chasing of the animals—and placed in a bucket of water, then poured from the bucket into a wire strainer and thence dumped into the 10-litre glass storage bottle. This was placed in a deep tank of running water under a shelter for from 15 to 29 hours. The contents of the bottle

TABLE IV.—Attempts to change established directions of swimming. B, 40 fish; LC, 20 fish; SC, 10 fish.

Experimental procedure	Apparatus	Schools tested	Total tests	Direction altered
Remained in apparatus overnight	B	8	8	0
	LC	10	12	1
	SC	7	7	0
Remained in apparatus two (once three) nights	B	4	4	0
	LC	2	2	0
Seined from apparatus, placed in storage bottle under cover overnight (15–29 hr.) before returning to the same apparatus at a different time of day	LC	15	17	2
Startled in opposite direction, original course reinitiated but complete circuit interrupted three times by startling in this way	B	2	9	0
Water almost all splashed from apparatus creating waves and more water then added	SC	4	5	0
Poured out into bucket and returned after 10 min.	SC	4	4	0
Water paddled 2 min. to startle fish and create strong positive rheotaxis in direction opposite to established course	B	2	9	0
Strong flow of water in direction of travel, usually reverses direction of fish (positive rheotaxis) —15 min. —30 min.	LC	7	7	0
	LC	5	7	0
Strong flow of water in direction opposite to course of travel, usually increases force of swimming in same direction—15 min.	LC	6	8	1
Moved apparatus to different locality	SC	6	7	0
Covered completely with waxed translucent paper	SC	5	7	0
Direction established under waxed paper and paper removed	SC	4	4	0
Moved from apparatus SC to apparatus LC	...	4	4	0
Moved from apparatus LC to apparatus SC	...	4	4	1
Total	...	99	145	5

were then poured rapidly through a wire strainer and the fish thus captured dumped again into the quiet water of the circular channel. Time of day was *never the same* and weather conditions usually quite different. Sometimes the fish moved immediately in the direction established on the previous day. Sometimes they showed the varied type of behaviour described previously for schools first introduced to this apparatus but eventually resumed the original direction of motion.

DISCUSSION

These experiments clearly show that the picture of downstream migration previously developed for pink and chum salmon fry was incomplete (Hoar, 1951, 1954). Not only is the behaviour of schooling fry—used in all earlier studies—

different from that of nocturnal migrating individuals which have never schooled, but definite directions of swimming are probably established and may possibly be maintained independently of rheotactic responses. Contradictions between Neave's (1955) and Hoar's (1951, 1954) observations should not be attributed to feeding or to changes in phototactic and rheotactic behaviour but to the highly adaptive change in behaviour which occurs when the fish school for the first time. In everyday language it seems to mean that after the fry have schooled they no longer seek the protection of gravel and stones but rely on the protection of the school and its associated advantages. Factors which control the rate of emergence from the gravel and the extent of nocturnal migration remain to be investigated.

The second part of the paper presents evidence for rapid learning of fixed directions of swimming. The phenomenon of swimming in a clockwise or counter-clockwise direction is probably of little significance. However, the ability to establish and maintain a constant direction of movement may be fundamental to the migratory behaviour of these fish. Although it may be argued that the salmon in these circular channels are not going any place in particular, it cannot be denied that they are maintaining their directions in a surprisingly precise manner.

Mechanisms responsible for fixed directions of orientation have now been investigated in several groups of migrating animals. Bees fly to distant sources of honey and return using the rays of the sun to guide their course (von Frisch, 1950). The beach flea uses the sun and the moon to maintain its direction of hopping with respect to the shore (Papi and Pardi, 1953; Pardi and Papi 1953). Starlings and pigeons may use the sun in navigation (Kramer, 1953). In the case of chum salmon the sun may also be of importance but these preliminary experiments lend little support to such a theory. At present it appears that these directions are initiated and maintained independent of the sun but may be fixed in some way by currents of water. However, it should certainly not be concluded on the basis of the experiments recorded here that the fixed direction will be a counter-current direction. Directions are just as easily established in quiet water. In these experiments rheotaxis, either positive or negative, is not necessarily involved. It is tentatively suggested that strong stimulation of many types may establish a direction of swimming, which will be maintained until some stronger stimulus re-orientates the animal. Such a mechanism would give scope for orientation through optic, olfactory and gustatory sense organs as well as the acusticolateralis system. It is too soon to speculate on mechanisms which maintain such fixed directions of swimming.

This study emphasizes the importance of learning in the behaviour of juvenile pink and chum salmon. Experiments reported in both sections of the paper demonstrate rapid and stable changes in behaviour. The nature of the learning process is unknown. However, similar sudden and permanent changes in behaviour—for example, imprint learning (Lorenz, 1935)—have been described among birds and fishes (Thorpe, 1950).

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Interspecific Competition and Population Control in Freshwater Fish^{1,2}

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ABSTRACT

Interspecific competition is defined as the demand of more than one organism for the same resource of the environment in excess of immediate supply. When two species are "competing for a niche" the term competition has been used to include phenomena such as predation of the two species on each other, competition to avoid a parasite, etc. Making this distinction in natural situations is unrealistic. In the limited sense in which interspecific competition is defined above, it is a discrete phenomenon, which with other phenomena such as predation, can be measured as a factor involved in interaction between species.

Freshwater environments offer comparatively few opportunities for specialization in fishes. In consequence many species have a relatively wide tolerance of habitat type, a flexibility of feeding habits and in general share many resources of their environment with several other species of fish. Cannibalism and mutual predation are common complications of competitive relationships between species. The organization of freshwater fish communities is thus characterized by breadth at each level of the food chain rather than by a height of a pyramid of numbers. Flexible growth rate and high reproductive potential permit fish populations to tide over unfavorable periods of competition. In these circumstances it is difficult to separate the role of interspecific competition from other phenomena as a factor of population control. As a subordinate factor, predisposing fish to loss from other causes, interspecific competition may act to influence population levels. There is need for quantitative data and mathematical models for study of the types of population interaction typical in freshwater fish associations.

INTRODUCTION

THERE IS relatively little literature which deals directly with the subject of interspecific competition in freshwater fish populations. It is mentioned in texts, referred to in papers on population changes, but as a phenomenon has not been brought into such sharp focus as for other animal groups (for instance Crombie, 1947, and several other workers for insects; Udvardy, 1951, and Lack, 1946, for birds). The absence of reviews on the subject as it relates to freshwater fish may be because competition as a phenomenon is not well defined in the group, because it is difficult to demonstrate, because it is not important in freshwater fish relationships, or perhaps because it has escaped attention.

These aspects will be discussed in this paper in the light of knowledge of freshwater fish and their environment and a glance at literature pertaining to population phenomena in other animal groups.

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THE PHENOMENON OF INTERSPECIFIC COMPETITION

To indicate the boundaries of the subject of interspecific competition it is useful to consider some of the ways in which the phenomenon has been treated. Darwin's "The Origin of Species" contained a definition of competition as the demand, typically at the same time, of more than one organism for the same resources of the environment in excess of immediate supply. Competition occurs when the ratio of population to environmental resources reaches a certain value (Crombie, 1947). This type of definition is easy to visualize as it pertains, for instance, to *competition between individuals* at one time for a given item of food. It is also commonly used to describe *competition between populations* of animals for food or space or some other aspect of the environment which may be in limited supply.

In visualizing the relations between *populations* of two species of organisms "*competing for a niche*" it may seem necessary to enlarge the meaning of the word *competition* to include an adequate description of the interplay of longevity and fertility factors of all kinds favoring one population at the expense of another (Elton, 1946). Thus the effect of one population on another would be measured in terms of the degree to which one of the groups was able to take over the limited environment from the other, whether it be by eating more, breeding more, or living longer (or any combination of these or other factors) than the opponent population. Interactions between two populations "*competing for a niche*" could also be said to include other phenomena that are not usually conceived as mechanisms of competition. Thus in competition between sheep blowfly populations (Ullyett, 1950) predation of one species of blowfly on another influences the outcome of competition particularly at higher levels of density.

The mechanisms involved in competition of two populations for a niche can become more varied when the effects of a third species on the two competitors are considered. A predator for instance may find one prey species more easy to catch, and by its predation may determine the course of the competitive relationship. (Meek, 1930, regarding work of Petersen; Udvardy, 1951.) In a sense the two prey species could be described as competing to avoid the predator (Crombie, 1947). The same is true for parasite host interactions such as those described by Park, Gregg and Lutherman (1941) for granary beetles. *Tribolium confusum* usually won out in competition with *Gnathocerus cornutus* but when the *Tribolium* population was reduced by an epidemic protozoan infection, *Gnathocerus* exterminated *Tribolium*, i.e. *Gnathocerus* competed successfully in resisting the parasite. This type of argument could be extended to cover any factor which one way or another differentially affected one of two populations contending for a common position in the structure of an animal community. In studies of animal communities it is not uncommon to visualize that populations "compete for survival" under the conditions dictated by the environment. Because the multitude of relationships between animals in food chains and food cycles brings every animal in direct or indirect contact with each other animal, it is argued that every activity of each animal in a community in one way or

another constitutes an act of competition with all other members of the community (Clements and Shelford, 1939, p. 166; Udvardy, 1951). In fact, Nicholson (1933) uses the word "competition" to describe all types of density dependent animal interactions, whether predation, parasitism or competition for food, space or other factors. Rounsefell and Everhart (1953) distinguish between predation and competition (p. 46 and glossary) defining competition as an "indirect effect (excluding predation)". However, in discussing examples (p. 257) predation is called "the factor" in competition between undesirable species and sockeye salmon (Foerster and Ricker, 1941).

Considering *competition between species* over the whole of their ranges could require appreciation not only of competition between populations of the species in restricted localities, but also an understanding of factors of geographic distribution and rates of evolution both for the species concerned and the association of which they are a part.

The word competition has thus been used to describe a great variety of concepts of animal interactions. It has been used as a term to describe relationships between individual animals, between animal populations, or between species of animals. It may be used simply to describe demand at the same time for a particular material in limited supply, or it may be used to summarize the whole relationship between two species. Because competition has been given so many meanings it is difficult to single out one phenomenon which can be described as competition in the same sense that predation or parasitism can be defined. The word competition as it is now commonly used would always need qualifying with respect to what the competition was for and what size groups were involved before it was evident what mechanisms might legitimately be considered as part of the relationship. Thus competition for food between individuals would not involve predation; whereas competition for a niche between populations might involve predation of one competitor on another.

To properly qualify what competition was for and what size groups were involved might be difficult. To decide whether competition for a niche was occurring between animal populations, it would be necessary to define a niche, and as Riley (1953) states "the niche concept has been defined so broadly that it often literally means anything—usually an undetermined something". Any decision about what competition between populations was for would have to be based on an evaluation of its consequences. Only when it was known that one animal had eliminated the other and occupied the niche previously held by the other would it be justifiable to include phenomena such as predation among the mechanisms of competition.

There are no problems of this kind in studies of laboratory populations that are forced to compete for a narrow artificial niche sufficiently limited in the resource in common demand that the situation must be resolved quickly. In these experiments, if one species eliminates the other, and subsequently makes use of the environment then whatever mechanisms were involved in the elimination (e.g. predation) are the machinery of competition. If one species does not eliminate the other then the two species may be said to occupy partially separate

niches but that they compete with each other (for example for food) and a certain amount of predation occurs.

The probability of making the same subtle distinction in natural populations seems quite remote and particularly unrealistic. As Crombie (1947) has so abundantly indicated, there are a host of factors in natural environments which influence competitive relationships and their outcome. He classifies these factors under the heading "factors tending to reduce competition". The same material could be entitled "factors preventing the precise definition of a competitive relationship between populations". Briefly, Crombie's arguments can be construed to indicate that the organism itself, the physical environment or the biological environment may all change so much during the course of competition between two populations, that it is unlikely that the relationship will be positively resolved in favor of one species or another.

In summary our arguments have been:

- (1) Competition is the demand, typically at the same time, of more than one organism for the same resources of the environment in excess of immediate supply—
- (2) Competition between populations for a niche can be said to include in addition to competition for food, space, etc., such mechanisms as (a) predation by the competitors on each other; (b) competition for survival under the influence of predation, parasitism or any other factors of environment which differentially affect the competitors—
- (3) the inclusion of the mechanisms indicated in (2) as the machinery of competition is predicated on a knowledge of the final outcome of the competitive relationship—
- (4) the natural situations in which competition between populations may occur are so complex and varied that the final outcome of competition cannot be predicted as required in (3) above.

It thus seems fair to conclude that the word competition should be restricted to have only the limited meaning of (1) above. Interspecific competition is only the demand of more than one organism for the same resource of the environment in excess of immediate supply. In this sense it is a readily defined phenomenon, one of the mechanisms involved in the resolution of *interactions* between populations. If one species eliminates another from an environment and subsequently occupies the niche of the other, it may do so by competition, predation, environmental conditioning etc. The whole relationship should not be called interspecific competition.

CHARACTERISTICS OF FRESHWATER FISH COMMUNITIES

The typical morphology and physiology of fishes and the typical environment of fishes predispose them to certain types of competitive relationships. There seems to be general tacit agreement that the fresh water environment constitutes a distinct entity, a major subdivision of the broad categories of habitat type. Elton (1946) describes freshwater communities as a type consisting "mainly of a few ecological groups, each broadly drawing upon the same natural

resources for its basic food, with of course the usual predator parasite food cycles rising from it". He also remarks on the relative shortness of food chains in fresh water communities and their general similarity to the simple terrestrial communities of Arctic and Sub Arctic areas. Herbivores in fresh water communities are seldom restricted to one or a few plant species (Hesse, Allee and Schmidt, 1951). In fact, Kreckler (1939) found that aquatic freshwater invertebrates were most abundant on those aquatic plants which afforded them the best purchase! This situation is in contrast to some types of complex terrestrial associations in which there are a large number of monophagous herbivores and in consequence of which there are greater possibilities for ecological differentiation. Hesse, Allee and Schmidt (loc. cit.) remark also on the vague demarcation of ecological zones in freshwater environments. Moreover, there is no sharp demarcation of fish faunas with ecological zones. A wide range for fish is characteristic and many forms occur both in lakes and streams. Freshwater communities would seem to be characterized more by breadth than by height in the pyramid of a food chain; a complexity in "horizontal organization" (Elton 1946).

The pattern of distribution of plants and animals in freshwater communities may also be singled out as a difference from some types of terrestrial communities. In typical forest communities the trees greatly exceed the size of even the largest animals. In consequence different communities can be distinguished at different levels from the tree tops to the forest floor. Each zone may be characterized by a peculiar fauna as well as by a particular microclimate. While a similar type of stratification exists in lakes it is of an entirely different kind. Plant cover is only afforded at the margins of the uppermost stratum, setting it aside as the littoral zone, a separate community from the epilimnion in the open water area. In freshwater lakes there is little in the way of a substitute for the cover and the diversity of opportunities for niches that are provided for the animals inhabiting a forest. By comparison with the complex type of population interspersed described by Elton (1949) for a forest community, the spatial organization of plants and animals in a lake is extremely simple.

Characteristics of the freshwater environment are abundantly reflected by the habits of fishes. The lack of specialization in feeding habits among freshwater fishes has been noted by many workers. Forbes' (1914) general statement that fish have a common body of food resources which many of them draw upon according to circumstances but that there are tendencies to specialize which go in various directions to various stages, is as sweeping a generalization of the subject as any that has been written since. Hartley (1948) observed that members of a fish community were distinguished by no more than the varying proportions they drew from the common stock of food. The same observation can be gleaned from many studies of foods of fishes (for example Starrett, 1950; Webster, 1941; Clark, 1943; Clemens *et al.*, 1923). The food habits of fishes of the western end of Lake Erie summarized by Langlois (1954) are a particularly good example. Of the 55 species of fish listed, 37 shared insect larvae as food, 34 shared the Entomostraca as food. In only a few cases were food types confined in their occurrence to less than 10 species of fish, and in these instances

the food types were extraordinary (birds, mammals, amphibians) or inconsequential (mites, rotifiers). In no case were these special food items the sole diet or even a major portion of the diet of the fish concerned.

Attempts to classify fishes by their food habits are noteworthy for their brevity and the qualifications attached to them. Hartley (1948) lists 4 groups of feeding types in a stream community (1) specialist predators (2) insect and plant feeders (3) insect and crustacean feeders (4) wide variety feeders. Clemens *et al.* (1923) list 5 groups from Lake Nipigon (1) predators (2) bottom feeders (3) plankton feeders (4) shallow water plankton and bottom fauna feeders (5) insect feeders. Langlois (1954) suggests 5 groups for fishes of the western end of Lake Erie (1) phytoplankton and debris eaters (2) zooplankton feeders (3) insect and scud eaters (4) crayfish eaters (5) fish eaters. All of these workers indicate there is much overlap between groups. Food habits change with age of fish (for example see Boesel, 1938; Ricker, 1930; Northcote, 1954; Larkin and Smith, 1954; Leonard and Leonard, 1949). The young of most species share an early plankton diet, from which they proceed to larger food items. Food habits vary seasonally and the consumption of some food items may be significantly higher at some seasons than at others (Webster, 1954; Larkin *et al.*, 1950; Stroud, 1949). Two species may eat the same foods for only a small part of the season and only in some years. Many workers have concluded in effect that most species of fish eat what they have the opportunity to feed on, although such generalizations must be taken with reservation since selection of preferred foods has been suggested for some fishes at least (Lachner, 1950; Pearse, 1924; Ricker, 1937). Starrett's (1950) study of food habits of minnows in the Des Moines River suggests reason for doubt that stomach contents of fish reflect choice or lack of choice of food. He suggests that it is difficult to establish competitive relations between fishes for food because fish may change diet "rather than enter into severe competition". The ability of fishes to change their diet to take abundant foods and to compensate for absence of their usual diet by taking some other food is suggested as an important factor in regulating abundance of various fish species. In summary, studies of food habits of fish suggest chiefly that flexibility and adaptability are the usual rule, and that clear cut cases of a demand on a readily defined mutual supply are rare.

The possibility exists that different species effectively separate themselves spatially—i.e. each eating the same foods but in different parts of a lake. For example, it is common to think of lake herrings as part of an open water association in contrast to bottom feeding fish like the whitefishes or suckers (Clemens *et al.*, 1923). Though all forms may feed on Entomostraca they are taking them in different places and hence are not actually drawing from a common supply. Similarly, fishes found in the littoral zone can be considered as an association discrete from the open-water fishes (Clemens *et al.*, 1939). However, these divisions on the basis of ecological zones or habitat are inclined to be as arbitrary as divisions on the basis of food habits, and are characterized by the same type of overlapping of one group on the other. Hesse, Allee and Schmidt (1951) have already been cited in this respect. Eschmeyer and Clark (1939) remark on the

broad habitat preferences of fish populations in the waters of the Mason Game Farm, Michigan. Nash (1950) using the type of bottom to distinguish habitats could demonstrate associations between certain species, but again no clear cut spatial separation of species by habitat was possible. The brief account of Langlois (1954) of seasonal changes in distribution of fish in a lake indicates that while the different species of fish may be separated spatially at any one time by their habitat preferences, their seasonal movements are sufficient either to bring them into contact temporarily with other species or to put them where other species were present only shortly before. Thus while fish may typically be ascribed to a particular ecological zone they are not confined to that zone either as a whole at any one time nor as sub-groups distributed in the same way at different times.

✓ It is certainly evident that relationships between species of fish vary greatly from place to place. Part of this diversity stems from lack of specialization in freshwater fishes, part from the great diversity in lake and stream conditions, and part from the relative rapidity with which ecological succession proceeds in a lake (by comparison with the ocean for instance). These three parts may all be manifestations of the same thing. Much of the diversity of freshwater environments is related to the shape and size of lake basins, the gradient and substrate of streams, characteristics, which in terms of geological time periods are extremely short lived. Specialization in such impermanent environments would be untenable, particularly considering the difficulties fish would have in moving to similar habitats when conditions changed. Freshwater environments are thus noted for variation at the race and subspecies level rather than at higher systematic strata, except for the few extremely long prevailing lakes such as Lake Baikal and Lake Tanganyika (each of which has a substantial endemic fish fauna). With the majority of species venturing only part of the way along the route of specialization, and with the background of diversified environment, variability in interspecies interaction is to be expected. Moyle (1949), Krumholz (1950), Bennett (1944), Swingle (1949) and Carlander (1952) have all mentioned that certain species combinations which occur widely have different suitabilities for pond fish culture in various parts of the United States. Larkin (1954) indicates that interactions between Kamloops trout (*Salmo gairdneri kamloops*) and other species are probably not the same in different types of lake environments. Pearse (1934) on the basis of a study of six quite dissimilar lakes stated that each lake presents a type in which one or more species of fish may be at their best and become dominant. It is important to note, however, that while certain species of fish may not find all freshwater environments suitable, they nevertheless tend to persist, with various degrees of success in a considerable variety of the habitat types available.

— There are other features of fishes as an animal group which greatly influence competitive relationships. It is a common observation that fish have elastic growth rates which reflect the environment in which they live. Beckman (1941) described change in growth rate of rock bass following reduction in population density. Swingle and Smith (1941) mention growth adjustments to population

density of bluegills, black bass, white crappies and bullheads in ponds that can support only a limited poundage of fish. Mottley (1941) describes changes in the growth rate of Kamloops trout related to population density. Regardless of how these growth changes come about, they represent a phenomenon of adjustment to competition which is not available to many groups of animals. Under adverse conditions the automatic adjustment of growth rate reduces the intensity of competition and permits a "tiding over" until more auspicious conditions recur.

Coupled with the flexibility of growth rate, fish share a relatively high reproductive potential. While retarded growth rate may make inroads on egg production, the number of eggs is usually sufficiently large that even a relatively small number of small fish are capable of producing a large brood to capitalize on any improvement in conditions. Thus, fish are equipped both to tide over unfavorable periods and to seize an opportunity when provided.

In summary, freshwater environments are characterized by the lack of opportunity they offer for specialization of animals. This feature is reflected in versatility and plasticity of fishes, and the consequent vagueness and complexity of interrelationships between fish species. It might be predicted that the effects of interspecific competition (defined in the limited sense previously indicated) would be difficult to segregate from this complex.

DEMONSTRATING INTERSPECIFIC COMPETITION IN FRESHWATER FISH POPULATIONS

★ In view of the foregoing remarks regarding the nature of freshwater fish associations it would be anticipated that there would be general agreement that it is difficult to demonstrate phenomena of interspecific competition in fish and even more difficult to follow their course. Thus while Nikolsky (1945) as cited by Hartley (1948) claims that interspecific competition is the main problem of ichthyology, Lagler (1944) was prompted to conclude that fish managers "are confronted with a vastly great unknown—knowledge of the effects of these relations" and further "Studies demonstrating exact effects of competition in the various forms in which it exists are few in our literature" and "to date our work is almost entirely qualitative and superficial in nature".

Competition between individual fish can be demonstrated rather simply. Extrapolating these observations to a measure of competition between populations is considerably more challenging. Three types of competition between fish have been most studied (1) for food (2) for space (3) for spawning site.

COMPETITION FOR FOOD. This may occur between individual fish but while individuals may have the same food, and on occasion two fish may actually compete for the same food item, it is by no means sure that there is any measurable competition between populations for a limited food supply. In essence this observation has been made by several workers (Van Oosten, 1944; Lagler, 1944; Hartley, 1948; Starrett, 1950) who have emphasized that the fact that different species of fish eat the same foods is not just cause for assuming they are competing (i.e. as populations).

COMPETITION FOR SPACE. The common phenomenon of growth rate adjustments to population density may be due to competition for food between individuals, but there has been the suggestion that other agencies, sometimes lumped in the term "space factor" may be operative (Hile, 1936). Territorial behavior, aggressive behavior and social dominance are well recognized aspects of fish ethology (Stringer and Hoar, 1955; Noble and Curtis, 1939; Newman, 1956). Study of fish behavior will no doubt contribute greatly to appreciation of competitive relations for space between individuals of different species.

COMPETITION FOR SPAWNING SITES. This has been discussed by Lagler (1944) and by Bailey and Lagler (1938) particularly from the viewpoint of observations that sterile hybrids may be produced in proportion to the numbers of the parent species of sunfishes involved. In addition to hybridization, competition for spawning site in minnows may result in reduction or failure of spawning for the less aggressive species (Reighard, 1943). There is possibly greater chance for competition of this kind to occur between closely related species. Moreover, there would appear to be greater specialization in breeding habits than in food habits. Langlois (1954) classifies spawning habits into eleven groups, considerably more subdivisions than are available for food habits. Fish spawn seldom, many species only once a year, while feeding is a much more continuous activity. Thus competition for spawning site will probably occur much less frequently than competition for food. However, when there is loss through competition for spawning site the effects are liable to be considerably more damaging to a population than occasional and temporary competition for food. There is great need for quantitative study of effects of this type of competition.

EFFECTS OF COMPETITION

Despite the difficulties of demonstrating competition between populations as evidenced from the meagre material mentioned above, it seems certain competition does occur as measured by its end result. Lagler (1944) states that the "coarse fish problem" is one of the best realized competitor problems. Rounsefell (1946) and Rawson (1952) both give bases for computation of poundage of fish that can be produced in lakes of various types. The concept of "carrying capacity" of lakes and streams is widely accepted by fishery managers (Moyle, 1949). A great deal of literature on pond fish culture is concerned with the effects of non-game fishes on production of game fish (Bennett, 1952; Smith and Swingle, 1939; Swingle and Smith, 1941) and it is established that in various degrees, production of one species is curtailed by the presence of one or more competitor species. "Lake rehabilitation" is the popular euphemism for wholesale poisoning of coarse, trash or rough fish that reduce production of game species, and its spectacular results in many areas attest to the depressing effect that the non-game species have had on the desired species. In some cases the competition between populations takes the form of habitat despoilment as well as food consumption. Species such as carp (*Cyprinus carpio*) may roil the water, root out aquatic vegetation and in general change the whole nature of the environment. The effects of such species is most intense in shallow lakes (Bennett, 1944). Like

some plant species which shape the characteristics of some plant communities, these fishes are often referred to as "ecological dominants" (Cahn, 1929). Even partial removal of these species can be rewarded by improvement in angling for desired species (Ricker and Gottschalk, 1941).

Thompson (1941) describes a different kind of dominance, that of crappies (*Pomoxis* spp.) of a large year-class which through their lifetime apparently by predation and competition for food dominate the abundance of all species of fish in a lake. The balance of bluegill and largemouth bass combinations extensively treated by Swingle (1950) often has the unsatisfactory end point of the "crowding out" of the bass by the overly numerous and stunted bluegills, partly by competition for food and partly by predation. Regarding these species, Bennett (1952) found that bass alone would produce 50 lb./acre of a standing crop, bluegills alone 200 lb./acre, but in combination the two species produced a crop of only 220 lb./acre. He states that although they are not strong competitors the two species each may curtail the population of the other. Van Oosten's (1949) observation that the "rough fishes" of the Great Lakes only partly compensated for the decline in "fine fishes" reflected the easing of the competition of the fine fishes.

There is thus abundant evidence for inferring that competition between populations does occur, but there is surprising little evidence of the way in which it comes about and its role by comparison with predation and other factors. Understanding of the mechanisms and effects of competition for food, space or spawning site between populations requires separation and precise measure of (1) effects of competition between individuals (2) effects of predation by the competitors on each other and (3) differential effects of features of the biological and physical environment on the competitors, as each of these relates to the basic schedule of births and deaths which determines change in abundance from one generation to the next. At present there is little quantitative data of this type available.

DISCUSSION

Ignorance of the relative importance of competition as a phenomenon in fish populations is a handicap to both the fishery manager and the theorist of animal ecology. It is instructive to examine the broad perspective of animal interrelations as a whole to evaluate how big a handicap this is and what shortcuts can be taken to gauge the situation. One such method is by the construction of mathematical models which, based on reasonable assumptions, can indicate the probable consequences of certain types of situations. The most appropriate mathematical models for study of interspecific competition are the so called Lotka-Volterra simultaneous equations. (Lotka, 1932; Volterra, 1931). Treated by Allee *et al.* (1949) as a basic part of modern ecology, these same equations are described as basically inconsistent, nonsensical, and unrealistic by Andrewartha and Birch (1953). Regardless of their mathematical subtleties, as Riley (1953) has stressed, these models can reflect no more than the knowledge that goes into their assumptions. Conversely, inadequacy of the assumptions should be warning of the limits to application of their conclusions.

In their simplest form, the Lotka-Volterra equations require as assumptions or corollaries to assumptions several features that are noticeably deficient in freshwater fish competitive situations. For instance, they require that each individual in a population of species A regardless of age should have the same effect on individuals of species B. Moreover, the effect is instantaneous when each individual is either added to or removed from the population. The "carrying capacity" of the environment and the relative competitive advantage of the species must both remain constant over the course of the conflict. Growth of both populations must be continuous. In short, close approximation of the conditions required of the equations in their simple form will not likely be approached in natural communities of fishes. However, this is not to say that modifications of the Lotka-Volterra equations could not be devised to suit the situation if the data were available on which to base assumptions. While such models might be cumbersome they could be formulated and resolved as a vindication of the mathematical method regardless of complications. Presumably, work of theorists in population dynamics will proceed along these lines in the future, but at present there are no theoretical models which provide a sufficient skeleton for intense study of competition in fishes.

Riley's (1953) modifications of logistic growth equations which resolve a large proportion of the variability in production in marine plankton associations by adjustment for several major environmental factors, give promise of providing new generalizations about food chain relationships in ocean communities. Significant in this approach is the grouping of potential competition at any level of the food chain. Competition is thus sidestepped—classified temporarily as part of the unresolved variability.

The recent contribution of Ricker (1954) also does not mention interspecific competition, although it provides a mathematical model for interpretation of changes in abundance based on observed density-dependent relationships of a species. In Ricker's models agencies affecting abundance of a species are classified as density dependent or density independent. Effects of interspecific competition could fall in either category as they influence the species in question. Calling the model species A, then any increase in its numbers may increase (or decrease) losses due to interspecific competition for food, space etc. with species B. In this respect competition fits into the schedule of density-dependent factors. However, if species B increases, the effect on species A may depend partly on the abundance of species B, i.e. an effect independent of the density of A, or density-independent. Actually, of course, the effect of the two species on each other is a function of the densities of both in relation to the object of their competition, which in itself may be determined independently of the density of both species. In short, interspecific competition is not specifically considered in Ricker's treatment of population changes.

A second approach to evaluation of the relative importance of interspecific competition as a population factor in fishes can be made through considering examples in relation to the various theories of population control. Essentially, there are two schools of thought. One is contained in the works of Nicholson (1933, 1954) and asserts that density dependent factors only (some form of

"competition") can control animal populations. The other has been developed by several workers (e.g. Bodenheimer, 1938; Davidson and Andrewartha, 1948) but most recently has been emphasized by Andrewartha and Birch (1954) and maintains that climatic factors acting essentially in a density independent way control natural populations. (Andrewartha and Birch assert, however, that climate controls in a density dependent fashion.)

Various examples can be cited for climatic control of freshwater fish populations. Langlois (1954) explains fluctuations of lake herring populations of Lake Erie in terms of turbidity. Miller (1952) suggests that year-class strength in whitefish (*Coregonus clupeaformis*) in some Alberta lakes may be inversely correlated with strength of autumn winds which roll windrows of eggs upon the beaches. Larkin (1954) describes the effect of spring run-off characteristics of streams as they affect abundance of Kamloops trout. Explanations for fluctuations in abundance of marine fishes based on effects of oceanographic conditions are also well known (Riley, 1953). In many respects the dynamics of these types of fish populations may be similar to those of some insect populations, as described by Davidson and Andrewartha (1948) for thrips and Bodenheimer (1938) for various insects. In these cases populations of herbivorous insects fluctuate in accord with the vicissitudes of the physical environment as measured by rainfall, humidity, temperature etc. Presumably, the abundance of species predatory or parasitic follow the waves of abundance of the prey or host to the extent that it constitutes their sole source of living. In such situations interspecific competition, when it occurred, would be as unpredictable as the physical environment, but with little chance of being an important controlling factor. It would only occur when by chance two species with close habits were both abundant in relation to a limited environmental resource they both required.

Thus in some aquatic habitats and for some species of fish, climatic controls would seem to outweigh biological factors in controlling populations.

In aquatic environments that are physically more stable biological factors would undoubtedly be invoked as population controls. The limitation of population size by predators and competitors is abundantly demonstrated in reports of results of coarse fish control programs mentioned above. Intraspecific competition and cannibalism play similar roles in adjustment of growth rate and population size in single species populations of many species of fish as well as supplementing predation and interspecific competition in mixed populations of several species.

In development of an evaluation of various population phenomena as they influence speciation, Utida (1953) states: "In a natural community species interact with each other as host and parasite or as predator and prey, as well as by way of interspecific competition for the same niche requirements. Neither type of interaction can be ignored, and both kinds together provide the warp and the weft of community organization". Utida adds that "The regulatory action of inter or intraspecific competition can be transformed or outweighed by such higher order interspecific interactions as predation and parasitism". This expression of the relative importance and interplay of biological factors seems particularly applicable to the type of situation in freshwater fish populations. A relatively

simple example can be pieced together from observations made in some British Columbia lakes by Lindsey (unpub.) and Larkin and Smith (1954). The red-side shiner (*Richardsonius balteatus*) competes with small Kamloops trout for food. The growth rate of the young trout is slowed so that an extra season (or more) is spent in the size range where they may be vulnerable to predation by squawfish (*Ptychocheilus oregonense*). Interspecific competition is here a factor contributing to the intensity of predation. Several similar examples could be drawn from the literature. It is suggested that this role of interspecific competition, a role shared with intraspecific competition, may be one of its most important effects in freshwater fish communities.

In some aquatic environments, species similar in requirements may exhibit growth and survival rates which reflect interspecific competition for favorable habitat sites. The competition between species of trout in streams (Newman, 1956) is a notable example. In this case, competition between the species may be manifested directly by lowered egg production and indirectly by disposing those adversely affected to greater loss through cannibalism, adverse physical and chemical conditions and predation.

In conclusion the following synthesis is suggested. Freshwater environments offer comparatively little opportunity for specialization in fishes. In consequence many species have a relatively wide tolerance of habitat type, a flexibility of feeding habits and in general share many resources of their environment with several other species of fish. Cannibalism and mutual predation are common complications of competitive relationships between species. The organization of freshwater fish communities is thus characterized by breadth at each level of the food chain rather than by a height of a pyramid of numbers. With their omnivorous diets many species tap food resources at several levels of the food chain. By their flexibility of growth rate and high reproductive potential fish are well equipped to tide over unfavorable periods of competition. In such circumstances it is difficult to separate the role of interspecific competition from other phenomena as a factor of population control. As a subordinate factor, predisposing fish to loss from other causes, notably predation, interspecific competition may influence population levels.

There is great need for quantitative data on interspecific competition and for mathematical models designed to approximate the complex type of population interaction that is typical of freshwater fish associations.

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On the Specific Identity of the Larval *Porrocaecum* (Nematoda) in Atlantic Cod¹

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ABSTRACT

Larval *Porrocaecum* sp. commonly infect Atlantic cod (*Gadus callarias*) in Canadian waters. Some of these larvae are known to be young stages of *P. decipiens*, but this is not proof that only one species of *Porrocaecum* parasitizes cod.

The distribution of 13 marine species of adult *Porrocaecum* is reviewed. Only one species, *P. decipiens*, is known from Canadian Atlantic waters; its distribution is consistent with the distribution of infected cod.

The frequency distribution of the lengths of about 875 larval *Porrocaecum* from cod was examined, as was that of the lengths of the oesophagus, ventriculus, and intestinal caecum of about 200 larvae. These suggest that only one species is present in the samples.

Body proportions of larval *Porrocaecum* from cod agree more closely with those of adult *P. decipiens* than with those of 10 other marine species of adult *Porrocaecum*.

It is concluded that the larval *Porrocaecum* in cod are probably conspecific.

INTRODUCTION

LARVAL ascarids commonly parasitize the axial musculature of Atlantic cod (*Gadus callarias*) and other teleosts in Canadian Atlantic waters. The author has examined more than 1,000 of these ascarids ranging in length from 9 to 52 mm. With the exception of about 10 small worms from cod from the Grand Banks, all belonged to the genus *Porrocaecum*. The exceptional cases were either *Porrocaecum* in which the generic characters had not completely developed, or were the larvae of a closely-similar genus, *Anisakis*.

The absence of conspicuous morphological characters makes difficult the specific identification of larval marine ascarids. Accordingly, some larval worms were raised experimentally to maturity in young harbour seals (*Phoca vitulina*) and the adult worms were identified by Scott (1953) as *P. decipiens*. The experiments, however, did not prove that all *Porrocaecum* larvae in cod are *P. decipiens*. Indeed, the low percentage of recoveries of worms introduced into the seals led to two suggestions. First, harbour seals may not be the natural definitive hosts for *P. decipiens*. Secondly, more than one species of larval *Porrocaecum* may be present in cod, but only one of these species develops to maturity in seals. The first suggestion can be readily dismissed; there is ample evidence (Scott, 1950) that harbour and grey (*Halichoerus grypus*) seals in this area are common hosts

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for *P. decipiens*. The second suggestion will be discussed in this paper, and evidence will be presented to indicate that the *Porrocaecum* larvae in cod are conspecific. This information is needed before any rational attempt to reduce the incidence of the parasites in cod can be considered. If only *P. decipiens* is involved, a reduction in the number of seals might produce a decrease in the incidence of the parasite. If, however, more than one species of *Porrocaecum* is present in cod, the identity and contribution of each species to the infection in cod would have to be determined before a suitable program of control could be developed.

MARINE SPECIES OF PORROCAECUM

Let us assume that the *Porrocaecum* larvae in cod are not conspecific. Some will be *P. decipiens* with seals as their definitive hosts. For the remainder, however, there must be another definitive host. This host must be a predator on cod or at least on some fish which has the parasite. Furthermore, the distribution of this host should be consistent with the distribution of the parasite in the Maritime Provinces (Scott, 1950). It should be widespread and it should be more common in inshore than in offshore waters.

The four main groups of predators on marine teleosts are mammals, birds, other teleosts, and elasmobranchs. The literature dealing with the parasites of these groups has been surveyed to discover how many species of marine adult *Porrocaecum* are known, and also to find out how many species of *Porrocaecum* occur in the predators of the North Atlantic. In making this survey, the author relied chiefly upon the following reviews of the parasites of several vertebrate groups: Stekhoven (1935) on the vertebrates of the North and Baltic Seas; Baylis (1932) on the cetaceans of the world; Margolis (1954) on the marine mammals of the North Pacific; Cram (1927) on birds of the world; Yamaguti (1941c) on the birds of Japan; Yamaguti (1941a) on the fishes of Japan; and Punt (1941) on the fishes of the North Sea. Furthermore, Zoological Records from 1920 to the present were examined for references to *Porrocaecum*. As a result, the author believes that most, if not all, of the species of marine adult *Porrocaecum* are mentioned in this paper. In marine vertebrates the ascarids of mammals seem to be the best known; in contrast, those of elasmobranchs have been rarely studied. Undoubtedly, therefore, many species of *Porrocaecum* await discovery.

MAMMALS

Porrocaecum decipiens in Pinnipedia (Stiles and Hassall, 1899); in the sea-otter, *Enhydra lutris* (Rausch, 1953); and in a porpoise, *Phocaena phocaena* (Schmidt-Ries, 1939).

P. kogiae in the pigmy sperm whale, *Kogia breviceps* (Johnston and Mawson, 1939). This whale is only rarely found in the North Atlantic (Miller and Kellogg, 1955).

The genus *Porrocaecum* has not been recorded from about 25 other species of cetaceans (Baylis, 1932; Stekhoven, 1935; Yamaguti, 1941b; Margolis, 1954). In Canadian Atlantic waters, the genus has not been observed in the white

whale, *Delphinapterus leucas* (Lyster, 1940). The parasites of other whales in this area are unknown.

BIRDS

P. phalacrocoracis in a Japanese cormorant, *Phalacrocorax capillatus* (Yamaguti, 1941c), is the only record of *Porrocaecum* from any bird which could conceivably be considered as an important marine predator on fish.

The genus was not found in other water birds that have been examined for parasites, as follows: eleven species of cormorants, one of penguins, two of loons, four of grebes, four of tubinares, three of mergansers, nine of gulls and terns, and three of auks (Cram, 1927; Stekhoven, 1935; Johnston, 1937; Yamaguti, 1941c).

Throughout the Maritime Provinces and Maine, the double-crested cormorant, *Phalacrocorax auritus*, frequently feeds on smelt, *Osmerus mordax*, which are commonly infected with larval *Porrocaecum*. Nevertheless, *Porrocaecum* was not found by the author among ascarids in the stomachs of cormorants from the Miramichi estuary, New Brunswick, and from Maine.

TELEOSTS

P. secundum in *Trichiurus lepturus* from the South Atlantic (Lent and Teixeira de Freitas, 1948);

P. draschei in *Arapaima gigas*, a South American freshwater fish (Baylis, 1927).

Adult *Porrocaecum* have not been found in any boreal Atlantic teleosts, although the parasites of many of these fishes have been studied (Stekhoven, 1935; Punt, 1941; Dollfus, 1953).

ELASMOBRANCHS

P. ginglymostomae in *Ginglymostoma cirratum* from Florida (Olsen, 1952);

P. chiloscyllyi in *Chiloscyllium punctatum* and *Emissola antarctica* (= *Mustelus antarcticus*) from the east coast of Australia (Johnston and Mawson, 1951a);

P. cephaloscyllyi in *Cephaloscyllyium umbratile* from Japanese waters (Yamaguti, 1941a);

P. antarcticum in *Mustelus antarcticus* from the coast of New Zealand (Leiper and Atkinson, 1914);

P. galeocerdonis in *Galeocerdo tigrinus* from the Indian Ocean (Thwaite, 1927), and in three Australian sharks (Johnston and Mawson, 1951b);

P. scoliodontis in *Scoliodon* sp. from the coast of Queensland (Baylis, 1931);

P. rochalimai in a Brazilian shark (Pereira, 1935);

P. pristis in *Pristis perotteti* from the Hughli River, India (Baylis and Daubney, 1922);

P. pastinacae in *Dasyatis pastinaca* from the Bay of Biscay (Dollfus and Desportes, 1945).

At least two other species of *Porrocaecum* may occur in elasmobranchs. Baylis and Daubney (1922) thought that an ascarid, *Ascaris circularis*, found by

von Linstow (1907) was probably a *Porrocaecum*. This worm was in a West African sawfish, *Pristis antiquorum* (=perotteti?). In 1901, Linton described *Ascaris brevicapitata* from a tiger shark, *Galeocerdo tigrinus*, taken near Woods Hole, Massachusetts. Baylis (1931) believed that this species might be a species of *Porrocaecum* closely related to *P. scoliodontis*. If Linton's species was a *Porrocaecum*, it would be the northernmost record of the genus from an elasmobranch in the western North Atlantic.

The genus was not recorded by Stekhoven (1935) in four sharks and five rays from the North and Baltic Seas, or by Punt (1941) in three sharks and three rays from the North Sea. Moreover, Yamaguti (1935, 1941a) did not observe *Porrocaecum* in five sharks and four rays in Japanese waters.

Little is known about the parasites of Canadian Atlantic elasmobranchs. Heller (1949) did not observe *Porrocaecum* in *Squalus acanthias*, *Raja erinacea*, *R. scabrata*, or *R. laevis* although her work was carried out in a region where cod are heavily infected with larval *Porrocaecum*. Heller, however, examined only 26 specimens, of which 20 were *R. scabrata*, so that her results are inconclusive.

To sum up, the genus is represented in marine hosts by at least 13 species, of which nine appear in elasmobranchs. One mammalian host, the pigmy sperm whale, is accidental in this region and therefore has no bearing on the present discussion. One species occurs in a cormorant, but the genus has not been found in other cormorants including the double-crested cormorant which is a predator on smelt in the Maritime Provinces. This bird can surely be disregarded as an important host, if it is a host at any time, of *Porrocaecum* in these waters. The only marine teleost known as a host for adult *Porrocaecum* is a sub-tropical and tropical species. There is no evidence to suggest that boreal Atlantic teleosts are hosts for adult *Porrocaecum*. Elasmobranchs appear to be the most probable hosts for our hypothetical species of *Porrocaecum*. There are, however, some facts which reduce this probability.

First, none of the known elasmobranch hosts of *Porrocaecum* occur commonly in east-coast Canadian waters (Vladykov and McKenzie, 1935; Bigelow and Schroeder, 1953). Secondly, there are no records of *Porrocaecum* in the two genera, *Squalus* and *Raja*, of elasmobranchs that occur commonly in our waters. Finally, the distributions of the spiny dogfish, *Squalus acanthias*, and four common species of *Raja* are very different from the geographical distribution of larval *Porrocaecum*. The larvae are most abundant in inshore cod, particularly those of the Gulf of St. Lawrence, and are scarce in offshore cod. Dogfish and skates, on the other hand, are widely distributed in both inshore and offshore areas (Vladykov and McKenzie, 1935; Bigelow and Schroeder, 1953). If any of these species was a normal host of *Porrocaecum* from cod, then the difference in the incidence of infection between inshore and offshore cod should not be as great as the observed difference. Furthermore, the distribution of infected cod corresponds closely to the distribution of two important definitive hosts of *P. decipiens*, the harbour seal, *Phoca vitulina*, and the grey seal, *Halichoerus grypus*.

In conclusion, seals are the only known predators on teleosts in the boreal

Atlantic which are commonly hosts to a species of *Porrocaecum*. The only species of *Porrocaecum* recorded from seals is *P. decipiens*. This evidence suggests that the *Porrocaecum* larvae in cod are all *P. decipiens*.

ANALYSIS OF MORPHOMETRIC DATA ON LARVAE

Species and subspecies of animals may often be distinguished by differences in body dimensions. If the frequency distribution of a dimension of an organ is plotted and a bimodal curve results, the sample is not homogeneous. Moreover, if variations in sex, age, or other sources of variation in a single population do not account for the bimodality of the frequency distribution, then the sample has probably been drawn from more than one population.

With the foregoing ideas in mind, the lengths of 875 living worms from cod caught in Baddeck Bay, Nova Scotia, have been analysed. Each worm was placed in a longitudinal groove in a rectangle of lucite which was then covered by a long glass cover-slip. The worm was measured under a binocular microscope by a rule graduated in half-millimetres. Otoliths were removed from each cod and the ages of the fish were determined by Miss Arlene MacMorran of the Biological Station, St. Andrews, N.B. Frequency-distribution histograms of the lengths of the worms for each age-group of cod were made.

Measurements were also made of the body-length and the lengths of the oesophagus, ventriculus, and intestinal caecum of about 200 larval worms removed from cod that were caught in various parts of the Maritime Provinces. Similar measurements were made on about 50 adult *P. decipiens* that were recovered from young harbour seals (Scott, 1953). The worms were killed in hot 70 per cent alcohol, cleared in lactophenol, and mounted in glycerin jelly on slides. Each worm was photographed and then enlarged two times. The length of a worm was measured from the photograph by means of a pair of fine adjustable-dividers which were set with their points 2 millimetres apart. Repeated checks on representative worms indicated an error of less than 3 per cent. The digestive organs were measured microscopically with an ocular micrometer. The worms were grouped into 2-millimetre length groups and, for each of four groups, a frequency-distribution histogram of the length of each digestive organ was made. The histograms were examined for bimodality.

The usefulness of this method depends upon the existence of measurable interspecific differences in the characters studied. If such variation can be shown to exist in known species of *Porrocaecum*, then the method can be used with a reasonable expectation that measurable differences will be apparent if more than one species of *Porrocaecum* are present in the sample. The total length and the length of the oesophagus, ventriculus, and caecum in 20 species of *Porrocaecum* are contained in Table I.

Table I shows clearly that there is considerable variation in the length of the adults in different species. This suggests that even in larval worms there might be marked differences in length, differences which in a mixed sample might produce a bimodal frequency-distribution curve.

The lengths of the digestive organs also show much interspecific variation.

TABLE I.—Total lengths and the lengths of the oesophagus, ventriculus, and intestinal caecum of 20 species of adult *Porrocaecum*.

Species	Host	Authority	Total length mm.	Oesophagus mm.	Ventriculus mm.	Caecum mm.
<i>P. decipiens</i> , 20 ♂♂ and 22 ♀♀	Harbour seal, <i>Phoca vitulina</i>	Scott (unpub.)	31-78 mean: 48	mean: 2.4	mean: 1.4	mean: 1.2
<i>P. kogiae</i> , 1 ♀	Pigmy sperm whale, <i>Kogia breviceps</i>	Johnston and Mawson, 1939	15	2.0	0.4	Slightly longer than ventriculus
<i>P. ensicaudatum</i> , ♂♂ and ♀♀	Song-birds	Cram, 1927	28-58	?	?	Almost rudimentary
<i>P. spirale</i> , 1 ♀	Owls	Yamaguti, 1941c	50	2.3	0.3	1.0
<i>P. fulviducum</i> , 1 ♂ and 1 ♀	Dotterel, <i>Eudromias modestus</i>	Baylis, 1929	14-24	1.7-2.5	0.2-0.3	0.6-1.0
<i>P. angusticollis</i> , 2 ♂♂	Marsh hawks	Yamaguti, 1941c	55-56	2.7-2.8	0.4-0.5	2.2-2.3
<i>P. serpentinus</i> , 1 ♂?	Herons and cranes	Cram, 1927	55	3.4	0.4	3.0
<i>P. reticulatum</i> , 1 ♂	Herons	Yamaguti, 1941c	54	3.8	0.5	3.0
<i>P. phalarocoracis</i> , 3 ♂♂	Japanese cormorant, <i>Phalacrocorax capillatus</i>	As above	53-67	2.9-3.2	0.3-0.4	?
<i>P. phalarocoracis</i> , 1 ♀	As above	As above	65	2.6	0.4	2.2
<i>P. praelongum</i> , ♂♂ and ♀♀	Grebe, <i>Colymbus auritus</i>	Cram, 1927	90-154	4.3	0.4	3.0
<i>P. scandium</i> , 9 ♂♂ and 4 ♀♀	Marine teleost, <i>Trichurus lepturus</i>	Lent and de Freitas, 1948	20-31	1.8-2.4	1.7-2.2	Slightly longer than ventriculus
<i>P. draschei</i> , 1 ♂ and 1 ♀	Freshwater teleost, <i>Arapaima gigas</i>	Baylis, 1927	25-28	2.2-2.4	0.5	0.7
<i>P. rothallimai</i> , 1 ♂ and 1 ♀	Brazilian shark	Pereira, 1935	21-30	1.6	0.6-0.7	1.2-1.5
<i>P. ginglymostomae</i> , 2 ♂♂ and 1 ♀	Shark, <i>Ginglymostoma cirratum</i>	Olsen, 1952	18-22	1.2-1.6	0.5-0.6	1.1
<i>P. chilocylliti</i> , ♂♂ and ♀♀	Shark, <i>Chiloscyllium punctatum</i>	Johnson and Mawson, 1951a	37-50	2.4-2.6	2.7-3.6	2.5-3.6
<i>P. cephaloscylliti</i> , 1 ♂	Shark, <i>Cephaloscyllium umbratile</i>	Yamaguti, 1941a	67	3.5	1.7	2.2
<i>P. galeocerdonis</i> , ♂♂ and ♀♀	Shark, <i>Galeocerdo tigrinus</i>	Thuwaite, 1927	18-24	2.3-3.1	0.6-0.8	1.1-1.8
<i>P. scoliodontis</i> , 1 ♂	Shark, <i>Scoliodon</i> sp.	Baylis, 1931	67	4.7	2.6	ca. 4.0
<i>P. pristis</i> , ♂♂ and ♀♀	Sawfish, <i>Pristis perotteti</i>	Baylis and Daubney, 1922	7-27	1.7-2.1	0.6-0.8	0.8-1.3
<i>P. pastinacae</i> , 8 ♂♂	Sting ray, <i>Dasyatis pastinaca</i>	Dollfus and Desportes, 1945	62-67	5.8	0.6-0.8	0-1.0
<i>P. pastinacae</i> , 13 ♀♀	As above	As above	79-86	6.2-6.8	0.6	0-1.3

In species with lengths around 50 mm., namely *P. decipiens*, *P. spirale*, *P. angusticollis*, *P. serpentulus*, *P. reticulatum*, *P. phalacrocoracis*, and *P. chiloscyllyi*, the length of the oesophagus varies from 2.3 mm. in *P. spirale* to 3.8 mm. in *P. reticulatum*; the ventriculus varies in length from 0.3 mm. in *P. spirale* and *P. phalacrocoracis* to 3.6 mm. in *P. chiloscyllyi*; and the length of the caecum varies from 1.0 mm. in *P. spirale* to 3.6 mm. in *P. chiloscyllyi*. *P. decipiens* and *P. chiloscyllyi* can be distinguished from others of similar size by the relatively long ventriculus which both species possess. *P. decipiens* can be separated from *P. chiloscyllyi* by the fact that the oesophagus in the former is almost twice the length of either the ventriculus or caecum whereas in *P. chiloscyllyi* the oesophagus is shorter than either the ventriculus or caecum. If the entire group of 20 species is considered, *P. decipiens* is characterized by a relatively short caecum and by a relatively long ventriculus. This combination of characters is not obviously shared by any other species with the possible exception of *P. kogiae*. The range in length of this species, 15 to 30 mm. (Johnston and Mawson, 1939), does not overlap with that of adult *P. decipiens*.

Although the number of specimens of each species is too small to warrant any categorical statement, it seems that each species may have its own specific proportions. Even if this is not true, the fact that *P. decipiens* has distinctive proportions is sufficient for our purpose. Our samples almost certainly contain some larval *P. decipiens*. If they also contain another species of larval *Porrocaecum*, the dimensions of the two types will probably be different. Hence we may reasonably expect that these differences will produce bimodal frequency curves.

LENGTH OF BODY AND DIGESTIVE ORGANS

Figure 1 shows that, apart from age-group II fish, there is no distinct bimodality in the length-frequency curves. In age-group II cod there are three worms which are much shorter than the remainder. These are probably worms which have recently entered the fish and have not yet grown to the length of older worms. If, on the other hand, they represent an unknown species of small *Porrocaecum*, they should also be represented in the curves for older fish. This is not the case; only one or two small worms are present in each of age-groups III, IV, and V, and none is present in the oldest age-groups despite the larger samples of worms in these age-groups.

The uniformity of the distribution curves is noteworthy. In each age-group older than II, most of the worms range in length between 30 and 50 mm. and the mean lengths of the worms in each age-group are almost identical. The limits of size are clear-cut. In age-group II the lower limit for most of the sample is 30 mm. with an upper limit of about 42 mm. The younger age of these worms probably accounts for the lower maximum size. The constancy in the length-range of the worms in the remaining age-groups indicates strongly that only one species of worm is present in the samples.

There are some irregularities in age-groups III and older which suggest that the samples are heterogeneous. These irregularities, if they are not the

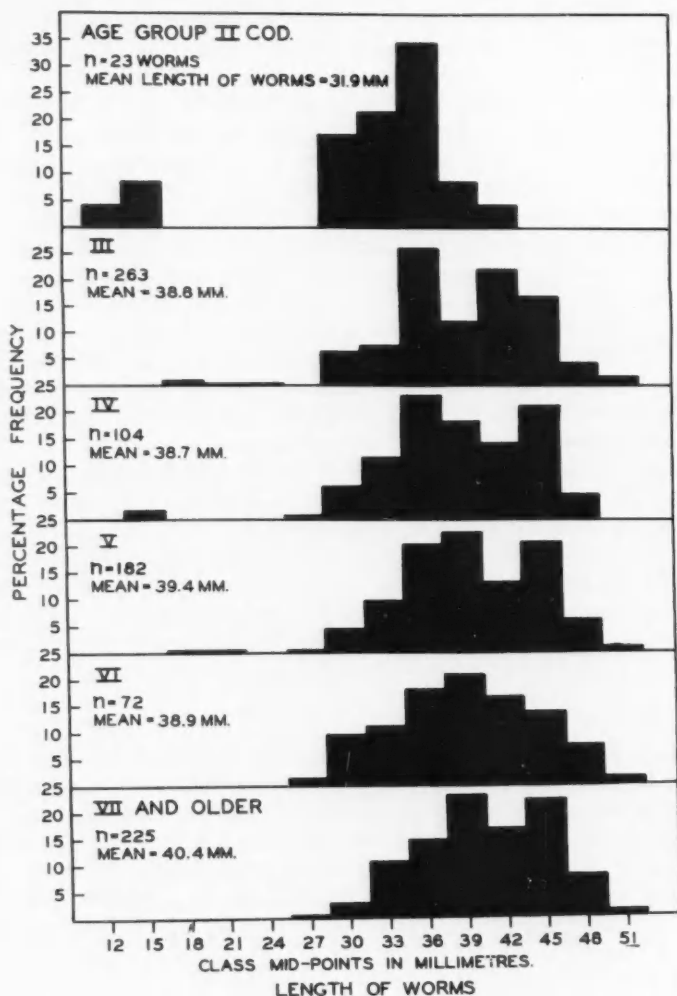


FIGURE 1.—Percentage frequencies of the lengths of *Porrocaecum* larvae from successive age-groups of cod caught in Baddeck Bay, Nova Scotia.

result of sampling errors, can be explained in terms of age and sex differences of the worms and there is no need to fall back on a mixed-species hypothesis to explain the irregularities. Since cod are continuously infected throughout life (Scott, 1949), each old age-group of fish should contain more than one age-group of worms. In young age-groups of cod, these groups of worms may be represented in the graphs by different modal lengths. For example, in age-group II

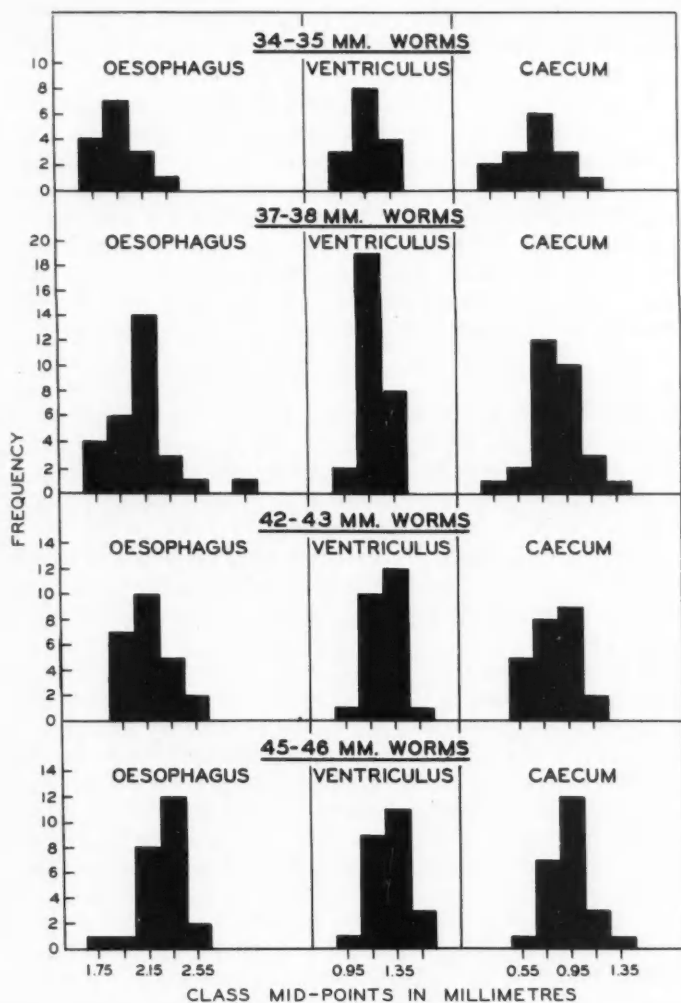


FIGURE 2.—Length frequencies of three digestive organs in four length-groups of *Porrocaecum* larvae from cod.

cod at least two age-groups of worms are apparently represented. In old fish, more age-groups of worms will be present, and the position of each age-group within the curve will be less obvious. This is precisely what happens in the curves in Figure 1. Bimodality, such as it is, is most apparent in age-groups II, III, and IV and is reduced or missing in older groups. Sexual differences in length may also explain some of the irregularities in the curves. Adult female *P. decipiens*

reach greater lengths than do the males. If this difference in size is present in the larvae, it might show up as an indistinct bimodality in the frequency-distribution curves.

There is no evidence from this analysis of the lengths of worms to support our original hypothesis. However, these samples were drawn from a limited geographic area and therefore our conclusion may not be of general application.

Figure 2 shows the frequency-distribution of the lengths of the oesophagus, ventriculus, and intestinal caecum in four length-groups of worms. All the histograms, with the possible exception of those for the oesophagus and the caecum of the 42 to 43 mm. group of worms, are essentially symmetrical. Bimodality is not evident in any curve. Therefore, there is no suggestion from these data that more than one species was present in the sample.

PROPORTIONS OF DIGESTIVE ORGANS

Relative-growth lines for the oesophagus, ventriculus, and caecum of about 200 larval *Porrocaecum* and about 50 adult *P. decipiens* are shown in Figure 3. These lines are based on equations calculated by the method of least squares. Plotted for comparison in the same figure are the values for the same digestive organs in the adults of 10 other marine species of *Porrocaecum*. The plotted values of the caecum of *P. kogiae*, *P. secundum* and *P. scoliodontis* are estimates derived from text figures or other descriptive material in the accounts of these species given by Johnston and Mawson (1939), Lent and Texeira de Freitas (1948) and Baylis (1931).

Larval *Porrocaecum* from cod have characteristics similar to those of adult *P. decipiens*, namely, a relatively long ventriculus and a relatively short caecum. The slopes of the larval growth lines are similar to those for adult *P. decipiens*. The digestive parts of the adult *P. decipiens* are relatively longer in most cases than those of the larvae, but, as Martin (1949) has pointed out, an increase in the size of a body part without any permanent alteration in the slope of the relative growth-line frequently follows critical periods in the life-history of an animal. The change in the worms from a larval to a reproductive phase could easily account for the differences in the position of the lines. The caecum of adult *P. decipiens* is relatively much shorter than that of any other species except *P. kogiae*. Most of the values for the caecum in the remaining species lie well outside the upper limit of the range in length of the caecum of *P. decipiens*. The lengths of the caecum in *P. phalacrocoracis* and *P. cephaloscyllii* lie at the extreme upper limit of the range for *P. decipiens*. The ventriculus, on the other hand, is relatively longer in *P. decipiens* than it is in most of the remaining species. The length of the oesophagus in most species is similar to that of *P. decipiens*. If all three parts are considered, only *P. kogiae* and *P. cephaloscyllii* closely resemble *P. decipiens*. However, the first two species have a caecum which is longer than the ventriculus, a condition which the writer has only once observed in larval *Porrocaecum* from cod and four times in adult *P. decipiens*. Moreover, the body-length of *P. kogiae* is much less than that of any adult *P. decipiens* examined. Indeed, it is even much less than the length of most larval

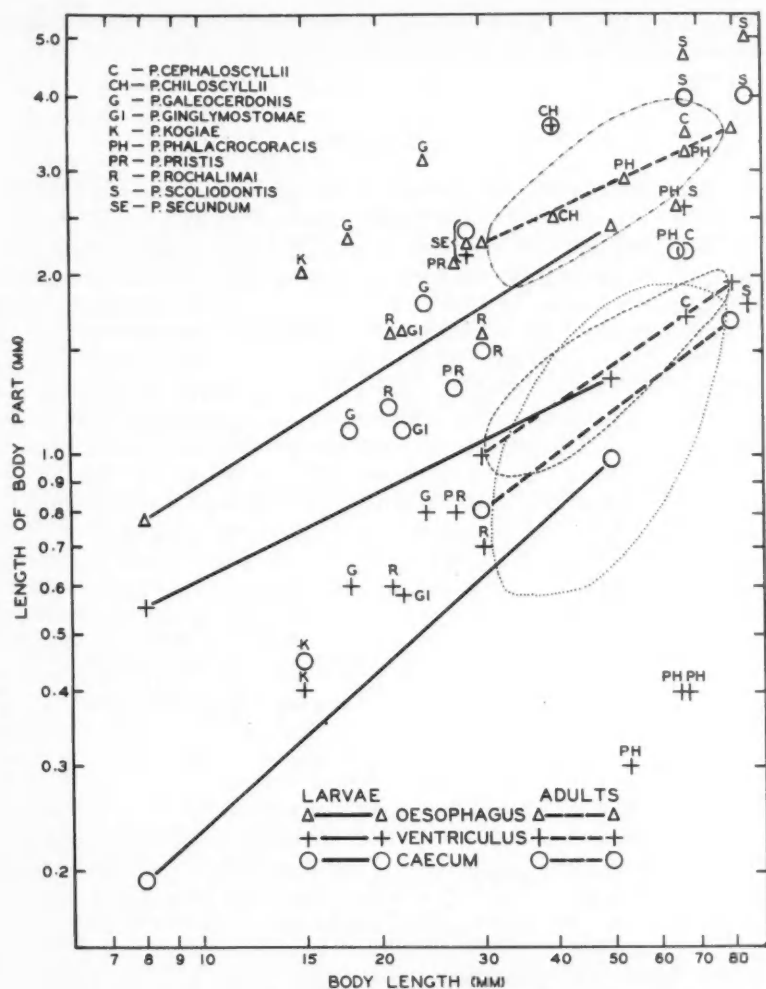


FIGURE 3.—Relative growth of three digestive organs in *Porrocaecum* larvae from cod (—) and in adult *P. decipiens* (---). The observed limits of variation are shown for the oesophagus (— · —), ventriculus (----), and caecum (.....) of adult *P. decipiens*. Lengths of these organs in adults of 10 other marine species of *Porrocaecum* are also shown.

Porrocaecum from cod, since, as we have seen in Figure 1, most *Porrocaecum* larvae in cod are longer than 30 mm. Considering both body-length and the proportions of the digestive organs, *Porrocaecum* larvae from cod resemble more closely adult *P. decipiens* than they resemble any other species shown in Figure 3.

In other words, the larval *Porrocaecum* in cod are either all young stages of *P. decipiens* or are a mixture of two species with similar body proportions. In view of the other evidence presented earlier, the former explanation appears more plausible.

DISCUSSION

A hypothesis that more than one species of *Porrocaecum* parasitizes cod was put forward at the beginning of this paper. Positive proof that the hypothesis is true would depend upon the discovery of another species of adult *Porrocaecum* in some common predator of cod or other teleost hosts of larval *Porrocaecum*. No such species is known. Moreover, the distribution of predators, other than seals, which might possess an undiscovered species of *Porrocaecum* are not consistent with the geographic distribution of larval *Porrocaecum* in cod. Secondly, the hypothesis would be supported if bimodality in the length-frequencies of the characters of the larval worms could be shown. This was not evident. Thirdly, the proportions of larval *Porrocaecum* resembled those of *P. decipiens* more closely than those of any other marine species of adult *Porrocaecum*. We may conclude therefore that our facts do not indicate the presence of more than one species of *Porrocaecum* in the axial musculature of cod. Only one species of *Porrocaecum*, *P. decipiens*, is known from Canadian east-coast waters. The distribution of its definitive hosts, seals, agrees closely with the distribution of infected cod. Consequently, as a corollary to our conclusion, all larval *Porrocaecum* in cod are apparently *P. decipiens*. However, complete substantiation of these conclusions cannot be made until the parasites of Canadian Atlantic predators, particularly the elasmobranchs, have been thoroughly studied.

ACKNOWLEDGMENTS

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Climatic Trends and Fluctuations in Yield of Marine Fisheries of the Northeast Pacific¹

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ABSTRACT

Mean annual air temperature at San Francisco, California, New Westminster and Masset, British Columbia, all had a rising trend from 1920 to 1940, then declined to 1950. Amplitude was greatest at Masset, least at San Francisco. The 20-years' rise is similar to the story in the North Atlantic ocean, but the recent decline has no parallel there. Prior to 1920 there were considerable differences among the above three stations. Mean annual ocean temperature at Nanaimo, B.C., is similar to air temperature at New Westminster since 1915. "Winter" ocean temperatures (February–April) show similar but not identical trends, and are thought to best represent conditions at the time eggs and larvae of most commercial bottom fishes are in the water.

Suggestive short-term correlations have been observed as follows: 1. a positive correlation between winter temperature and abundance of brill 6 years later; 2. a negative correlation between winter temperature and rock sole abundance 5 years later; 3. a negative correlation between winter temperature and strength of year-classes in lemon sole. Over a longer period, there is much resemblance between the temperature history since 1910 and the abundance of halibut broods, as indicated by catch per unit effort 10 years later (southern grounds) or 12 years later (Western grounds). The relationship is positive, and for western grounds is similar even in details. Over a somewhat shorter period, blackcod abundance has varied inversely with winter temperature. Marked changes in abundance and distribution of true (grey) cod since about 1900 cannot be related to temperature series available.

INTRODUCTION

DURING the past two or three decades much interest has arisen over evidence of a long-term warming of the Arctic and Subarctic zones in the North Atlantic. The phenomenon has been of far-reaching economic importance to the fisheries of that region, having resulted in marked changes in distribution and abundance of various foodfish stocks (Saemundsson, 1934; Taning, 1949, 1953; Fridriksson, 1949; Templeman and Fleming, 1953; and others).

In contrast, literature on the influence of climatic changes on fisheries of the North Pacific area is noticeably lacking. At first thought this might suggest that warming of the northern regions has been a phenomenon peculiar to the Atlantic area and that the Pacific area has been little affected.

It is the purpose of this paper to show that long-term changes in air and water temperature conditions have been occurring in the Pacific area and that these may be equal to or even greater than those witnessed in the North Atlantic. Scarcity of evidence on the effects of these changes is attributable mainly to the lack of suitable fishery statistics. Many marine stocks in the North Pacific have

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been exploited extensively for little more than a decade—too short a time to permit detection of long-term natural fluctuations. Among the few fisheries with long histories, some have undergone a long period of expansion to maximum production (e.g. blackcod) or have been severely affected by long-term changes in economic conditions (e.g. codfish). Another long-exploited stock, that of the halibut, apparently has undergone changes in abundance in consequence of overfishing and subsequent rehabilitation through management. It is possible, therefore, that important effects of climatic change on these stocks may have been masked by the influences of economics and the fisheries themselves.



FIGURE 1.—The coast of British Columbia showing some of the stations which record air and sea surface temperatures.

MATERIALS

Meteorological records of average air temperature, if not the most suitable indicators of climatic trends, are certainly the most popular tool of investigation. Along the British Columbia coast such records have been maintained for more than 50 years by the Meteorological Division of the Department of Transport (Canada). They are published by the Department of Agriculture for the province of British Columbia. For present purposes, two stations have been regarded as being representative of conditions off the south and north coasts of the province, namely New Westminster and Masset, respectively (Fig. 1).

Air temperature records from these stations have been compared with similar records from San Francisco, California. The latter have been approximated from graphs constructed by Hubbs (1948) from world weather records and Climatological Data of the United States Weather Bureau.

On the Pacific coast of North America records of water temperature have been maintained at several points but they go back little more than 40 years. Hence water temperature conditions in earlier times must be drawn by inference from the history of air temperature. Water temperature data for the British Columbia coast have been obtained from publications of the Pacific Oceanographic Group.

HISTORY OF MEAN ANNUAL AIR TEMPERATURE

Figure 2 shows the records of mean annual air temperature at three locations in the Northeast Pacific. In the graph for San Francisco a general increase in temperature is indicated from the beginning of the present century to 1941. During this period the mean (smoothed) rose from about 54°F. to 57°F. In the 30-year period prior to that shown, namely, 1850-1880, the mean temperature showed little difference from that prevailing at the turn of the century. This was in contrast to the situation at San Diego where, according to Hubbs, the mean declined noticeably between 1850 and 1900. From the beginning of the century to the present, however, the trend at San Diego has been similar to that at San Francisco. A slight decline was evident at both stations from 1941 to 1947.

The trend at New Westminster was downward from the turn of the century to about 1909. Thereafter the mean rose fairly steadily until approximately 1940. This was followed by a sharp decline between 1940 and 1950. The low point of 1909 corresponds with a secondary low point at San Francisco. Between 1909 and 1940, at San Francisco there was a three-degree rise in the smoothed mean, whereas at New Westminster it amounted to more than four degrees.

The picture presented by temperature records for Masset, B.C., is in contrast to those for the two stations farther to the south. Instead of following an upward course from the turn of the century, the mean declined by nearly four degrees between 1906 and 1922. From the low point established around 1922, the mean rose fairly steadily by more than four degrees to a peak around 1941. Thereafter there was a sharp decline paralleling that which occurred at New Westminster.

Although only three stations are considered here, there is the suggestion that progressing northward the fluctuations become more sharply defined. To

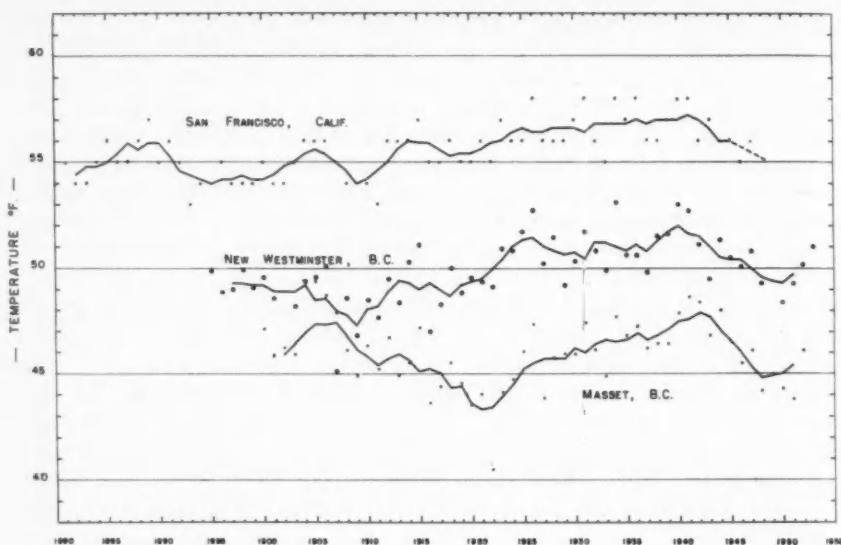


FIGURE 2.—Trends in mean annual air temperatures in the Northeast Pacific (lines smoothed by running averages of five).

establish this trend with certainty would, of course, require examination of records from more stations within the three main areas.

The difference between the trends at Masset and New Westminster does not appear to be the result merely of local peculiarities in climate. The sharp trend lines shown for Masset parallel closely those at other north coast stations (e.g., Bella Coola and Prince Rupert). In contrast, records from stations further to the south (Quatsino and Victoria) are similar to those from New Westminster. Off the British Columbia coast then, it seems that the trends have been sharper in northern regions than in the south and that the trough of low temperatures centering around 1922 was peculiar to the northern regions. This trough is evident also in data presented by Rounsefell (1930) for Seward, Alaska (about 800 miles northwest of Masset).

Changes in the rate of recession of the famous Muir Inlet glacier in Glacier Bay, Alaska, (Fig. 1) appear to conform with the trend of annual temperatures along the northern British Columbia coast. Graphic measurements of the recession, as illustrated by Ahlmann (1949) suggest the following approximate average rates: 0.85 km. per year between 1892 and 1907; 0.18 km. per year between 1907 and 1931; and 0.85 km. per year between 1931 and 1946. The slow recession during the middle period coincides with the period of low temperatures shown for Masset in Figure 2.

Ahlmann states that "... the glaciers in Alaska are now receding from terminal moraines formed during the period of maximum advance in the

eighteenth and nineteenth centuries . . . the summer temperature in the period 1935 to 1946 was higher than normal and though the total annual precipitation increased, the amount of annual snowfall decreased. . . ." Long (1955) reports that the return to cooler conditions in the late 1940's resulted in minor glacier extension in the north-western part of the United States.

The evidence of early moraine formation and recent recession suggests that the picture of annual temperature conditions shown for Masset was preceded by a period or periods of very much colder conditions during the nineteenth century.

HISTORY OF MEAN ANNUAL WATER TEMPERATURE

The longest record of sea water temperature history in British Columbia is provided by the station at Departure Bay (1915 to the present). The trend of mean annual temperatures at this station has been discussed by Tully (1950) and shows a somewhat irregular increase from 1917 to 1940 and a rapid decline between 1940 and 1950. This parallels closely the trend in air temperatures at New Westminster shown in Figure 2.

A comparison has been made between the history of water temperature at Departure Bay and that from one of the stations in the North Atlantic. The Departure Bay data are presented in Figure 3 as yearly averages of the monthly anomalies for the period 1915-50 and compared with similar data for the Faroe Islands (from Smed, 1951). The latter station is located at $62^{\circ} 06' N.$, $7^{\circ} 40' W.$ and hence at a considerably higher latitude than the Departure Bay Station ($49^{\circ} 12' N.$, $123^{\circ} 57' W.$).

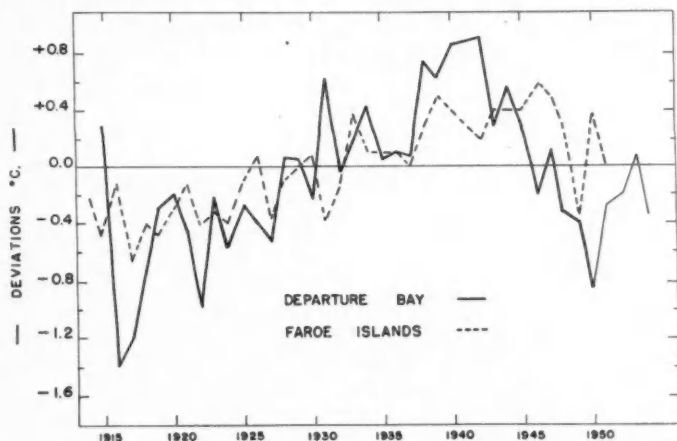


FIGURE 3.—Yearly averages of the monthly anomalies in the sea surface temperature at Departure Bay, British Columbia, and at Station Myggenaes, Faroe Islands.

The pictures are remarkably similar in that the majority of anomalies were negative prior to 1932 and positive in the years 1932-47. However, there are certain notable differences. In the first place, the gradient from negative to positive anomalies between 1917 and 1942 was steeper at Departure Bay than at the Faroes. Furthermore, the decline in temperatures which began after 1942 at Departure Bay and became very pronounced through the period 1943-50 is not represented in the trend at the Faroes (at least not before 1949).

The divergence of anomaly patterns during the 1940's at these two stations seems to be applicable to fairly wide areas of the North Pacific and North Atlantic. Data from the Northwest Atlantic, e.g. west Greenland (Taning, 1953), Newfoundland and New Brunswick (Templeman and Fleming, 1953; Lauzier, 1954), follow much the pattern of that for the Faroes in that no obvious downward trend in temperature has developed within recent years.

That a widespread decline has occurred in the Pacific area since 1940 is inferred by air temperature records from California to northern British Columbia. Water temperatures at latitudes higher than Departure Bay, for example at Triple Island in Hecate Strait ($54^{\circ} 18' \text{ N.}$, $130^{\circ} 23' \text{ W.}$) have paralleled closely those at Departure Bay (Fig. 4) and other British Columbia stations. Data presented by Hubbs (1948) show that at La Jolla, California, ($32^{\circ} 50' \text{ N.}$, $117^{\circ} 15' \text{ W.}$) the decline in water temperature has been noticeable only during the winter and spring months.

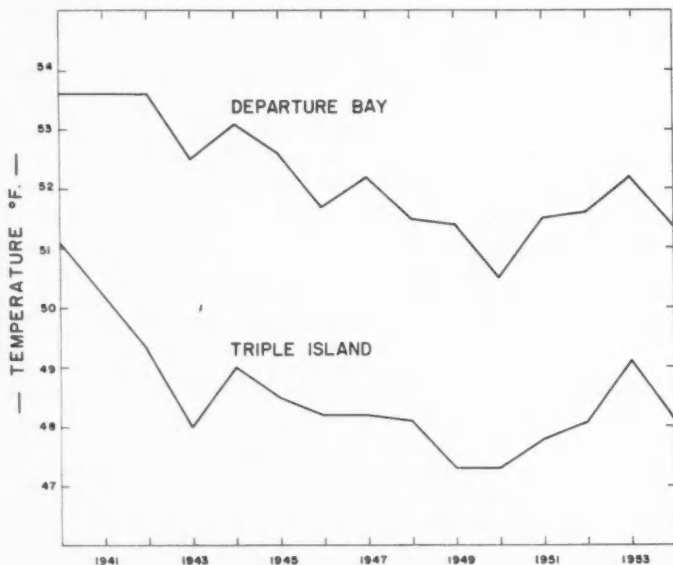


FIGURE 4.—Trends in mean annual sea surface temperatures at Departure Bay (southern coast) and Triple Island (northern coast), British Columbia.

HISTORY OF MEAN WINTER TEMPERATURES

Environmental events occurring during the winter months are probably of considerable biological significance to demersal fishes, since many of them spawn during or towards the end of the winter months. Their larval or pelagic stages (usually regarded as the critical stages for survival) occur mainly in the late winter and early spring. Hence, long-term changes in water temperature and (or) associated conditions at that time of the year may have a pronounced effect on abundance trends. Accordingly, an examination has been made of temperatures during the February–April period, since it covers more or less the period of the pelagic stage in several flatfishes, true cod and other groundfish.

Figure 5 shows the trend in February–April air temperatures at the California and British Columbia stations. In contrast to the data on annual temperatures, there has been close agreement among stations respecting the time of occurrence of peaks and troughs in the temperature trends. However, the dominant or primary peaks and troughs are not the same in all areas.

A notable difference between the winter and annual temperature trends was the occurrence of a dome of high temperatures between 1922 and 1936 in the winter months. At San Francisco and New Westminster the apex of this dome represented the maximum point in the advance during the period 1900 to 1946. At Masset, however, the 1922–36 dome of winter temperatures was of only

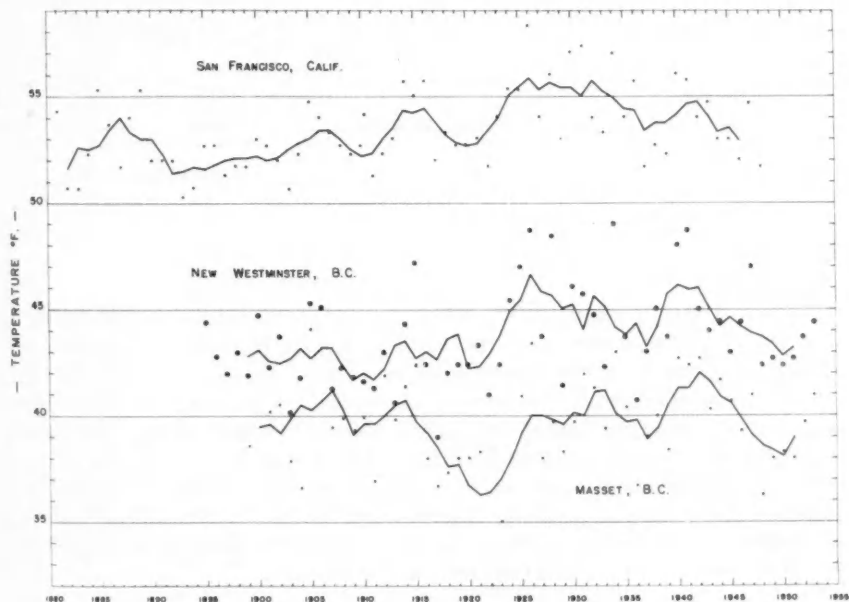


FIGURE 5.—Trends in mean "winter" air temperatures (Feb.–Apr., incl.) in the Northeast Pacific (lines smoothed by running averages of five).

secondary significance, being followed by a higher dome centering around 1942, which corresponded to the maximum of annual temperatures.

Water temperatures for the same time of year (Feb.-Apr., incl.) are shown for Departure Bay and Triple Island in Figure 6. Despite the proximity of Departure Bay to New Westminster the trends at the former station agree more closely with air temperature trends at Masset, in that the dome centering around 1930 was subordinate to that which occurred around 1940.

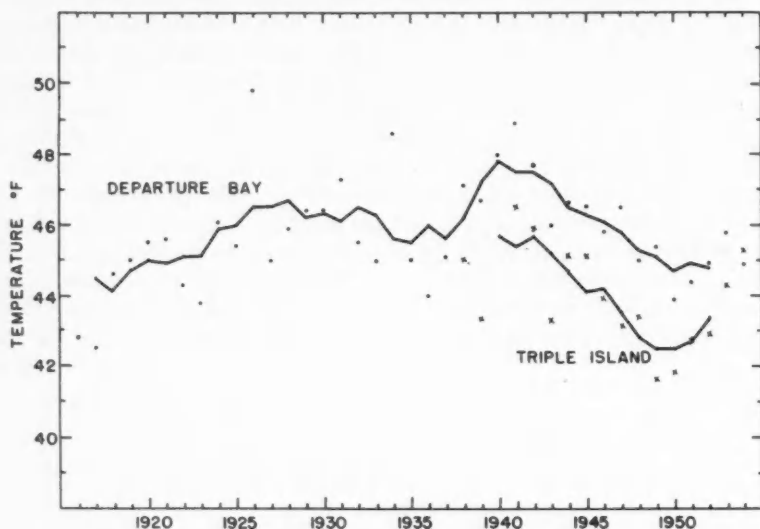


FIGURE 6.—Trends in mean "winter" temperature of the sea surface (Feb.-Apr., incl.) at Departure Bay and Triple Island, British Columbia (lines smoothed by running averages of five).

EFFECTS ON FISH ABUNDANCE AND DISTRIBUTION

Hubbs (1948) presents much qualitative evidence of changes in the distribution of marine organisms associated with long-term as well as single-season changes in temperature. Most of this pertains to United States waters, particularly off California. Intrusions of southern species of fish such as the California pompano (*Peprilus simillimus*) into British Columbia waters during periods of unusually high temperature have been recorded by Hart (1949).

Regarding groundfish species, it is difficult, as was pointed out earlier, to interpret the changes in catch or apparent distribution, in view of the variety of masking factors. However, there are some suggestive clues as to the effects which temperature trends may have had on abundance.

SHORT-TERM FLUCTUATIONS

First to be considered are short-term fluctuations in abundance which have become very noticeable in the trawl fishery of British Columbia during the recent

period of declining temperatures. Figure 7 shows inverse trends in late winter water temperature in Hecate Strait and in the catch of rock sole (*Lepidopsetta bilineata*) per unit of trawling effort when a five-year lag is applied to the latter data. The lag is based on evidence from age determinations that a rock sole year-class usually makes its maximum contribution to the fishery at an age of five years. While in the gross analysis this relationship lacks statistical significance, a negative correlation does indeed exist between detailed evidence of fluctuations in year-class strength and water temperature at the time of the pelagic stage.

It is well to emphasize at this point that, although discussion here and in later sections centres on the relationship of temperature to fish events, the writer does not wish to imply that a causal connection necessarily exists between the two. No matter how strong the correlation, proof of causation can be confirmed only by direct investigation of survival factors.

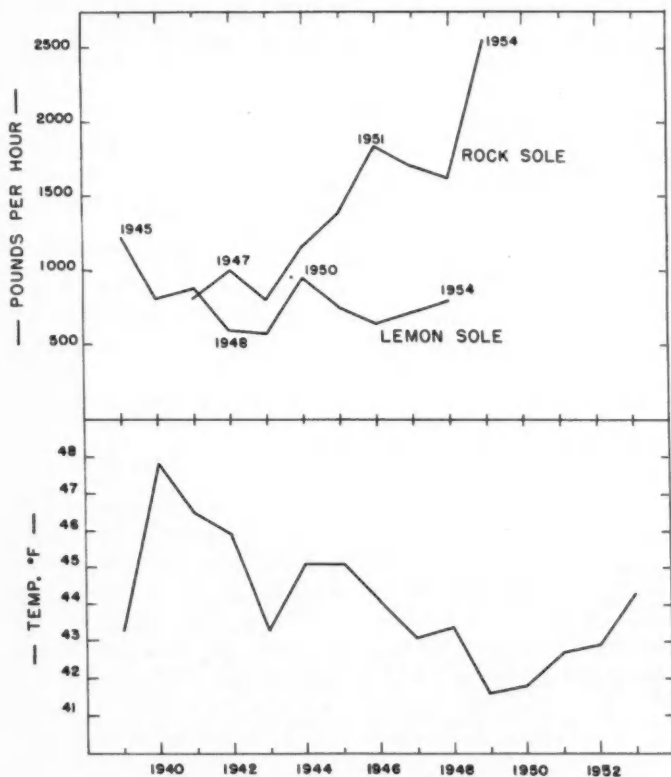


FIGURE 7.—The relation between mean "winter" temperature of the sea surface (Feb.-Apr.) in Hecate Strait and the catch/effort of rock sole and lemon sole five and six years later, respectively.

Catch/effort data for the lemon sole (*Parophrys vetulus*) have not followed the same trend as that exhibited by the rock sole, despite the fact that lemon sole year-class strength is correlated in a similar way with water temperature (Ketchen, 1956). This is explained by the fact that fluctuations in the strengths of lemon sole year-classes, while paralleling those of rock sole, have been of much lower magnitude (Ketchen *et al.*, 1951). Furthermore, factors other than abundance seem to play a much more prominent role in affecting the catch of lemon sole per unit of effort, particularly year-to-year changes in catchability. Marked irregularities in annual yield through changing fishing intensity have also contributed to the masking of the upward trend in survival.

The pronounced rise in availability of rock sole has occurred in the face of greatly increased fishing effort and annual yield, and hence the true change in abundance may well be greater than that illustrated by the index of catch/effort.

Off the west coast of Vancouver Island a very noticeable decline in the

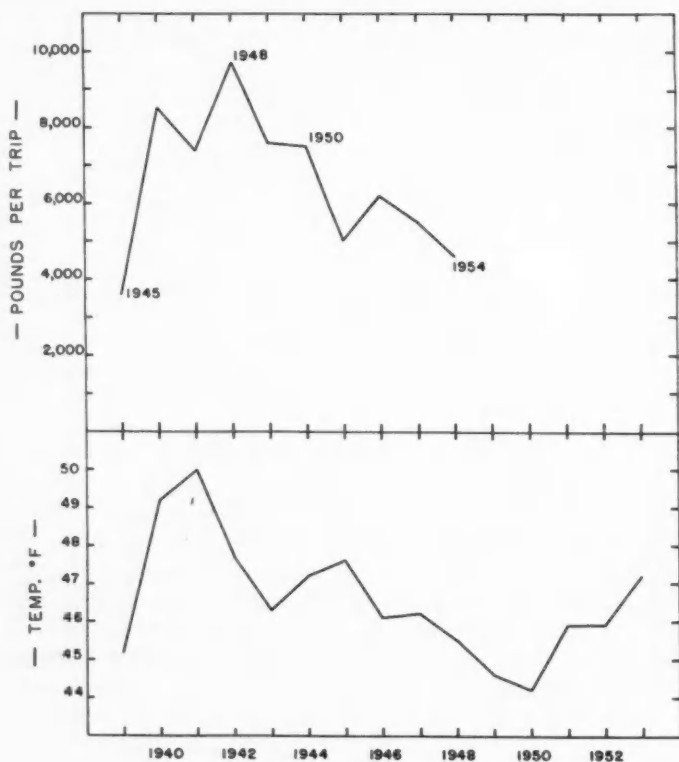


FIGURE 8.—The relation between mean "winter" temperature of the sea surface (Feb.-Apr.) off the west coast of Vancouver Island and the catch/effort of brill six years later.

trawl fishery for brill or petrale sole (*Eopsetta jordani*) has occurred within the period 1948-54 (Barraclough, 1954). Age and length composition show that this is clearly associated with a decline in the recruitment of young fish in the years since 1948.

The brill is about six years of age when it makes its maximum contribution to the trawl catch. In Figure 8 a six-year lag has been applied to the catch/effort data for the west coast of Vancouver Island and compared with late winter water temperatures for that area. A positive correlation is suggested. Events in the water temperature trend since the year 1948 point to continued poor recruitment and further decline in fishing success through reduction in the residual stock.

The suggested opposite reaction of the brill stock to that of rock sole in the presence of a downward trend in temperature is what one would expect in view of the difference in the geographical ranges of the two species. Northern British Columbia is about the northern limit of the range of the brill, in so far as commercially exploitable stocks are concerned. The normal centre of its distribution probably lies off the coast of the United States. In contrast, the rock sole is an inhabitant of much colder water, being distributed on both sides of the Pacific as far north as the Bering Sea. The southern limit of significant commercial stocks is along the central part of the British Columbia coast. Thus, it is reasonable to suppose that the brill would react unfavourably to declining temperatures (or associated factors) in the northern part of its range, while the rock sole would react favourably to the same trend in the southern part of its range.

LONG-TERM FLUCTUATIONS

The remainder of the discussion deals with fish stocks which have had relatively long histories of exploitation. Indices of changes in abundance of halibut (*Hippoglossus stenolepis*), blackcod (*Anoplopoma fimbria*) and true cod (*Gadus macrocephalus*) are compared in Figure 9 with mean annual and mean winter air temperatures for the northern coast of British Columbia.

HALIBUT (*Hippoglossus stenolepis*)

Much has been written about the long-term changes in the size of the halibut stock in the Northeast Pacific. The extensive work of the International Pacific Halibut Commission has seemed to provide evidence not only that the stock had been reduced seriously by fishing operations, but also that steps to manage the fishery were of considerable benefit in rehabilitation. Trends in abundance, as shown by records of catch per unit of effort for the western and southern grounds are plotted in Figure 9 from data presented by Thompson (1950), and Dunlop (1951).²

²Records for the years subsequent to 1948 are approximations interpreted from statements in Reports of the International Pacific Halibut Commission (Numbers 15, 16, 20 and 21). (Prior to Report No. 21, for 1953, this Commission was designated the International Fisheries Commission.)

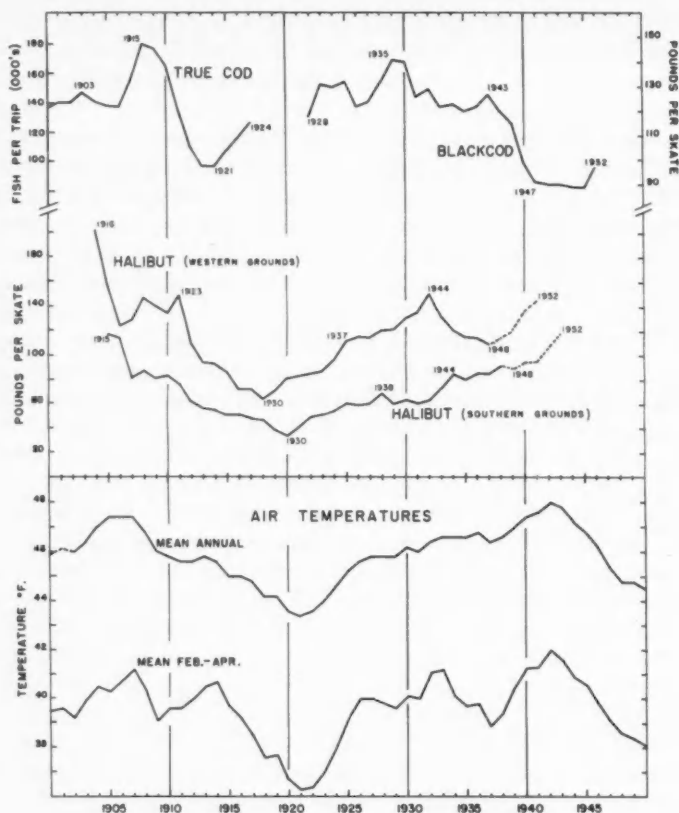


FIGURE 9.—Air temperatures at Masset, British Columbia, and their relation to trends in catch/effort of halibut, true cod and blackcod. For each species the catch/effort data are offset by the number of years equivalent to the approximate median age of contribution to the catch (see the text).

On the western grounds (those west of Cape Spencer) the halibut does not make a substantial contribution to the fishery until sometime between the age of 10 and 16 years (Internat. Pac. Halibut Comm., Rept. No. 21, p. 16), while on the southern grounds the fishery is dependent mainly on fish around 10 years of age. Accordingly, for present purposes a lag of 12 years has been applied to the catch/effort data for the western grounds, and 10 years for the southern grounds, in order to make a comparison with the air temperature history.

A good correlation exists between the mean annual air temperature and the catch/effort of halibut on the southern grounds 10 years later. The trend in catch/effort on the western grounds agrees in considerable detail with the trend

in winter air temperatures, particularly during the period when the stock was undergoing restoration.

Details of the relation between catch per skate and the number of skates during the depressed stage of the fishery led Thompson and Bell (1934) to conclude that fishing intensity was the dominating factor in determining the size of the stock. However, the hypothesis that long-term environmental trends have influenced the survival of young, can aid in the explanation of changes in catch/effort which are unaccounted for solely by the effects of fishing:

1. Burkenroad (1948) claims that removals by the fishery on the western grounds were insufficient to account for the observed rapid decline in abundance between 1915 and the early 1920's (particularly between 1915 and 1918). However, Thompson (1950) considers that inadequacies in the statistics for the early fishery, and changes in the character of the fishery itself, make it impossible to deal with events prior to 1924 as an integral part of the whole. While this may be true, it is possible that the general downward trend in temperatures 10 to 15 years prior to the rapid decline in apparent abundance may have been responsible for decreased survival of young.

2. Between 1936 and 1944 on the western grounds the recovery was more rapid than expected and Thompson attributes this to either natural factors or a change in gear efficiency. While he believes that the restoration of the spawning stock and consequent increased production of young would explain any natural change, there is also the possibility that more favourable (higher) temperatures in the winters between 1926 and 1936 led to increased survival of young.

3. Dunlop (1951) believes that the sharp increase in catch/effort on western grounds between 1940 and 1944 and the marked decline thereafter is related mainly to the pattern of fishing effort and economic conditions. While he believes that the passage of unusually strong year-classes may have played some part, there is a close correspondence between the trend in catch/effort and the winter air temperatures 12 years earlier. Possibly, therefore, natural factors predominated over the effects of fishing in forming this hump in the abundance curve.

BLACKCOD (*Anoplopoma fimbria*)

The trend in abundance of blackcod (or sablefish) shown in Figure 9 for the northern coast of British Columbia is derived from records of catch per skate reported by Ketchen and Forrester (1954). These data have been smoothed by threes and given a six-year lag to conform with preliminary observations that the offshore fishery is dependent mainly on fish which are five or six years of age (Edson, 1954).

There is a good negative correlation in considerable detail between catch/effort and the winter air temperatures, but the fishery may have influenced the abundance since the yield followed an upward trend in this period.

TRUE COD (*Gadus macrocephalus*)

During the latter half of the nineteenth century and the first two decades of the present century a schooner fishery for codfish was active in the Gulf of

Alaska and the Bering Sea. Records of the average number of fish per trip landed by California and Washington vessels have been reproduced in Figure 9 from tables published by Cobb (1926). Lack of detailed information on this fishery has prevented critical consideration of the effects of economic factors and changing gear efficiency on the trends illustrated. On the basis of age composition data presented by Mosher (1954) a seven-year lag has been imposed on the catch/effort data for comparison with air temperatures. In view of the unexploited condition of the stock at the time of Mosher's sampling, this lag may be excessive for interpretation of conditions earlier in the century. However, trials with shorter lags do not alter the impression that there is little detailed conformity between the fluctuations in catch/effort and temperature.

That the cod of the North Pacific has undergone noticeable change in abundance and (or) distribution in recent times is suggested in reports of explorations by the U.S. Fish and Wildlife Service. Ellson *et al.* (1949), in discussing the prospects for trawling in the Alaska and Bering Sea areas, state: "... one of the most interesting facts was the pronounced scarcity of codfish. The local inhabitants stated that while codfish were formerly very plentiful in the Kodiak area, now (1948) they are quite scarce. As far as the exploratory fishing was concerned their scarcity would seem to have been confirmed. . . ."

It is probable that this substantial change in distribution or survival has been brought about by some long-term change in the physical environment. Certainly, no fishery can be blamed for the recent scarcity. However, this scarcity is restricted to far northern waters, because otter-trawl fishermen of British Columbia and Washington have been enjoying an exceptionally fruitful fishery for codfish in recent years. The declining temperatures of the past decade may have shifted the northern limit of the range of the cod considerably to the southward and increased their abundance off British Columbia. However, this explanation seems to conflict with the inferences of conditions in the early part of the present century. Successful fishing occurred in the Bering Sea and Gulf of Alaska from 1905 to 1925 in the face of temperatures as low or lower than those which exist at the present time.

CONCLUSION

It is apparent from records of air and water temperature that long-term fluctuations in the marine climate have occurred along the British Columbia coast. They have been just as spectacular as those which have occurred in the North Atlantic, though they are not altogether parallel, especially in recent years. The relation of trends in the success of some of the marine fisheries to climatic trends is too suggestive to be ignored, and points to the need for more trenchant investigation of variations in the marine environment and its effects on abundance.

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APPENDIX

TABLE I.—Mean annual air temperatures (° F.) at New Westminster, British Columbia.

Year	Temp.	Year	Temp.	Year	Temp.
1878	50.3	1904	49.4	1930	50.3
1879	48.3	1905	49.6	1931	51.7
1880	46.0	1906	50.1	1932	50.8
1881	47.7	1907	45.1	1933	49.9
1882	...	1908	48.6	1934	53.1
1883	...	1909	46.8	1935	50.6
1884	...	1910	48.5	1936	50.6
1885	...	1911	47.7	1937	49.8
1886	...	1912	49.5	1938	51.5
1887	...	1913	48.4	1939	51.6
1888	...	1914	50.3	1940	53.0
1889	51.5	1915	51.1	1941	52.7
1890	...	1916	47.0	1942	51.1
1891	...	1917	48.3	1943	49.5
1892	...	1918	50.0	1944	51.3
1893	...	1919	48.8	1945	50.5
1894	...	1920	49.5	1946	50.1
1895	49.9	1921	49.4	1947	50.8
1896	48.9	1922	49.1	1948	49.3
1897	49.0	1923	50.9	1949	49.4
1898	49.9	1924	50.8	1950	48.4
1899	49.1	1925	51.7	1951	49.3
1900	49.6	1926	52.7	1952	50.2
1901	48.6	1927	50.2	1953	51.0
1902	48.9	1928	51.4		
1903	48.2	1929	49.2		

TABLE II.—Mean annual air temperature (° F.) at Masset, British Columbia.

Year	Temp.	Year	Temp.	Year	Temp.
1900	47.1	1918	45.5	1936	47.2
1901	45.9	1919	44.5	1937	46.2
1902	46.2	1920	43.5	1938	46.4
1903	45.9	1921	44.0	1939	46.4
1904	44.6	1922	40.5	1940	47.9
1905	49.4	1923	44.1	1941	48.6
1906	48.7	1924	44.7	1942	48.4
1907	47.9	1925	46.0	1943	46.8
1908	46.1	1926	47.3	1944	48.0
1909	44.9	1927	43.8	1945	46.5
1910	46.3	1928	45.7	1946	45.5
1911	45.2	1929	45.9	1947	46.1
1912	46.7	1930	45.9	1948	44.2
1913	44.9	1931	47.4	1949	44.3
1914	45.5	1932	46.1	1950	43.8
1915	47.2	1933	44.9	1951	46.1
1916	43.6	1934	47.7	1952	46.6
1917	44.4	1935	46.8	1953	46.3

TABLE III.—Mean February–April air temperature (° F.) at Masset and New Westminster, British Columbia.

Year	Temperature		Year	Temperature	
	Masset	New Westminster		Masset	New Westminster
1895	...	44.4	1925	41.0	47.0
1896	...	42.8	1926	43.4	48.7
1897	...	42.0	1927	38.0	43.7
1898	37.6	43.0	1928	39.7	48.4
1899	38.6	41.9	1929	38.3	41.4
1900	40.8	44.7	1930	39.7	46.0
1901	40.2	42.3	1931	42.0	45.7
1902	40.5	43.7	1932	41.3	44.7
1903	47.9	40.2	1933	39.4	42.4
1904	36.6	41.8	1934	43.0	49.0
1905	44.1	45.3	1935	40.4	43.7
1906	43.2	45.1	1936	36.7	40.7
1907	39.5	41.3	1937	39.0	43.0
1908	39.9	42.3	1938	40.0	45.0
1909	39.3	41.8	1939	38.4	43.7
1910	39.9	41.6	1940	42.7	48.0
1911	36.9	41.3	1941	42.4	48.7
1912	41.9	43.1	1942	42.7	45.0
1913	39.8	40.6	1943	40.3	44.0
1914	41.4	44.3	1944	41.7	44.4
1915	42.4	47.2	1945	40.7	43.0
1916	38.0	42.4	1946	39.3	44.4
1917	36.7	39.0	1947	41.0	47.0
1918	37.3	42.0	1948	36.3	42.4
1919	38.0	42.4	1949	38.0	42.7
1920	38.0	42.4	1950	38.3	42.4
1921	38.3	43.3	1951	38.0	42.7
1922	32.0	41.0	1952	39.7	43.7
1923	35.0	42.4	1953	41.0	44.4
1924	38.7	45.4			

TABLE IV.—Mean annual sea surface temperature (° F.) at Departure Bay and Triple Island, British Columbia.

Year	Departure Bay	Triple Island	Difference
1940	53.6	51.1	2.5
1941	53.6	50.2	3.4
1942	53.6	49.3	4.3
1943	52.5	48.0	4.5
1944	53.1	49.0	4.1
1945	52.6	48.5	4.1
1946	51.7	48.2	3.5
1947	52.2	48.2	4.0
1948	51.5	48.1	3.4
1949	51.4	47.3	4.1
1950	50.5	47.3	3.2
1951	51.5	47.8	3.7
1952	51.6	48.1	3.5
1953	52.2	49.1	3.1
1954	51.4	48.1	3.3

TABLE V.—Mean February–April sea surface temperature (° F.) at Departure Bay and Triple Island, British Columbia.

Year	Departure Bay	Triple Island	Year	Departure Bay	Triple Island
1915	48.0	...	1935	45.0	...
1916	42.8	...	1936	44.0	...
1917	42.5	...	1937	45.1	...
1918	44.6	...	1938	47.1	45.0
1919	45.0	...	1939	46.7	43.3
1920	45.5	...	1940	48.0	47.8
1921	45.6	...	1941	48.9	46.5
1922	44.3	...	1942	47.7	45.9
1923	43.8	...	1943	46.0	43.3
1924	46.1	...	1944	46.6	45.1
1925	45.4	...	1945	46.5	45.1
1926	49.8	...	1946	45.8	44.1
1927	45.0	...	1947	46.5	43.1
1928	45.9	...	1948	45.0	43.4
1929	46.4	...	1949	45.4	41.6
1930	46.4	...	1950	43.9	41.8
1931	47.3	...	1951	44.4	42.7
1932	45.5	...	1952	44.9	42.9
1933	45.0	...	1953	45.8	44.3
1934	48.6	...	1954	44.9	45.3

An Investigation of the Electrical "Spike" Potentials Produced by the Sea Lamprey (*Petromyzon marinus*) in the Water Surrounding the Head Region¹

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ABSTRACT

In the water surrounding the head of *Petromyzon marinus* electric triphasic spike potentials can be recorded which recur rhythmically at 0.4-second intervals and are synchronous with the externally visible movement of respiration. At a distance of 15 to 20 mm. from the animal, above the eye region, the potentials are from 200–300 μ v in an adult lamprey, in fresh water. The electric field produced by these potentials extends several centimeters frontwards of the head depending on experimental conditions and factors now being studied. Posterior to the gill openings the potentials taper off sharply and no spikes could be recorded 50–70 mm. posterior to the last gill opening. The field is symmetrical around the longitudinal axis of the animal under the experimental conditions described. Strychnine and cocaine do not affect the characteristics of the spikes but curare decreases their potential considerably, depending on amounts injected and the condition of the experimental animal. Light conditions do not affect the production of the spikes. The possible function of the electric field for the sea lamprey is discussed.

INTRODUCTION

UNDER contract with the Fisheries Research Board of Canada, an investigation was started in December, 1955 on hearing in the sea lamprey and on the effect of ultrasonic vibrations on this species in both the adult and larval stages.

As a preliminary to this work, a check was made to ascertain whether or not the adult sea lamprey produced an electrical field in the water surrounding its body. A preliminary note on the results of these observations was presented elsewhere (Kleerekoper and Sibakin, 1956). The present paper gives a more detailed account of these observations.

METHODS

Adult sea lampreys of 12–15 inches total length were placed in plastic tubes of 1½ inches diameter, a few inches longer than the animals. The initial experiments were made by using a black plastic tube which did not allow light to penetrate. Later experiments were carried on in rigid tubing of "lucite", a glass-clear plastic. Electrodes of silver wire were placed in these tubes along a straight, longitudinal line in the wall of the tube in such a way that about one millimeter of the wire was allowed to extend into the tube and about 15 mm. were left protruding outside the tube. By using an exact bore for the wire no sealing was required to prevent leakage of water. Each end of the tube was closed with a

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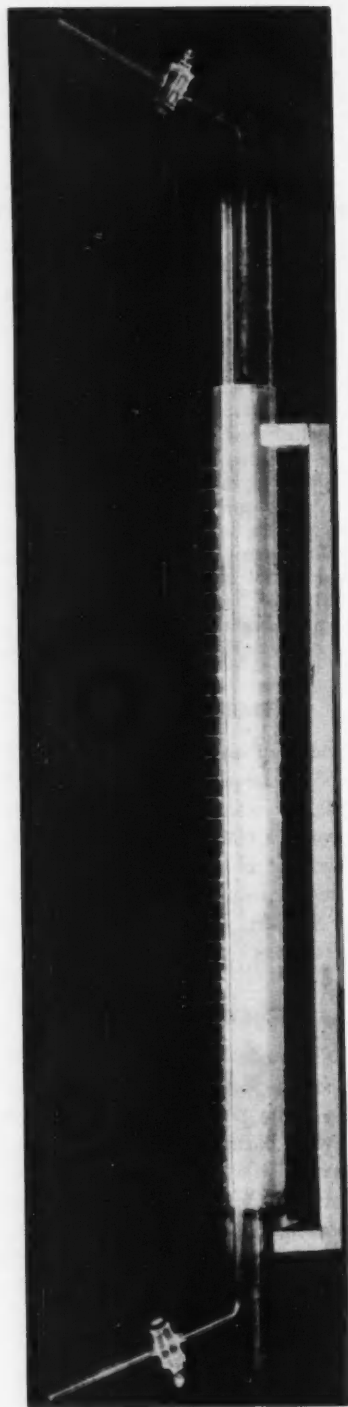


FIG. 1.—Double plastic tube with electrodes. See text.

glass stopper holding a short piece of glass tubing to allow for filling and draining of the tube. Each tube was held horizontally in a clamp with the electrodes on top in a vertical position. A lamprey placed in a tube would attach itself to the bottom or side surface of the tube and would therefore not touch any of the electrodes. After preliminary observations had been made with these tubes, a modified apparatus was constructed (Fig. 1). This consisted of two tubes, one fitting inside the other so as to make a water-tight fit. This was obtained by placing a thin leather piston at the extremity of the inner tube; the latter carries an electrode at its inner extremity which is connected to the outside by an insulated silver wire. This inner tube can be rotated or displaced longitudinally inside the outer tube without loss of water. The outer tube is again provided with electrodes of silver wire as described above, with the difference that not one but four rows of electrodes are inserted, making a 90° angle between each other. The outer extremities of both tubes are again stoppered and provided with glass tubing for the filling or circulation of water. In addition, the stopper of the outer tubing holds a plastic rod which protrudes inside the tubing where it holds a plastic disc of rough surface on to which the lamprey is to attach itself. This arrangement allows for the measurement of the electric field around the lamprey as well as in front of it.

In using either type of tube, care is taken to avoid air bubbles becoming lodged inside the tube with the lamprey. During measurements no water is allowed to flow into the tube and hoses are disconnected from the glass tubing at the extremities. The tubes, each holding one animal, were placed in a faraday cage containing also a D.C.-fed pre-amplifier with calibration circuit. One electrode at the far end of the tube behind the tail of the animal was used as a reference electrode, while any of the other wire electrodes were used as measuring electrodes. Both reference and measuring electrodes were connected with the pre-amplifier by means of shielded cables held at right angles to the tube. Pre-cautions were taken to prevent grounding of the tubes holding the animals. The output of the pre-amplifier was connected by a shielded cable outside the faraday cage to a dual-beam cathode ray oscilloscope. A kymograph camera was used to make either individual frame pictures or continuously moving film pictures of the oscilloscope screen. Both the oscilloscope and the camera were placed in a darkened space. An audio-generator with audio-amplifier and neon bulb were used to produce time signals on the camera recording. Very slow time signals ($\frac{1}{5}$ sec.) were produced by means of an interval timer and neon bulb.

The observations on the synchronous occurrence of the respiratory movements and spike potentials were made by means of motion pictures and high amplification of the spike potentials with pre-amplifier and audio-amplifier so as to produce the lighting of a neon bulb or the firing of a flash gun. The latter was used in connection with still photography in absolute darkness, maintaining the lens shutter open. For further details on this technique, the reader is referred to the text.

The techniques involved in the use of different drugs as described in the text do not require detailed discussion.

EXPERIMENTAL RESULTS

The initial experiment to ascertain whether the adult sea lamprey generates electrical potentials in the water surrounding its body were carried on in the manner described above. Using the black plastic tubing the experiment revealed at once the rhythmic recurrence of spike potentials in the water surrounding the head region. A typical spike recorded at that time is represented in Figure 2. By attaching the connecting wire to other electrodes on the tube it was clear that the spike potentials were not present throughout the tube. Wherever they occurred, however, they recurred rhythmically. Since it was not possible to observe the exact position of the electrodes in relation to the animal in the black opaque tube, subsequent experiments were made in the clear lucite tube.



FIG. 2.—Spike potential recorded in water surrounding the head of *Petromyzon marinus*. Electrode 8 mm. anterior of left eye, 15 mm. from the animal. Time signal 10 milliseconds. Spike potential 200 μ v. Third phase (positive) 30 μ v.

Observation of the animal in position in the transparent tube showed that almost invariably it would attach itself slightly sideways so as to have its left side upwards. Since it was not possible in this tube to rotate the electrodes in relation to the animal, most of the subsequent observations were made with the electrodes over the left side of the animal. Numerous observations from all electrodes in the tube, running from tail to head and beyond the head, showed clearly that the highest potentials recorded were those from the head region, specifically from the eye frontwards. Electrodes posterior to the eye produced recordings of spikes very much lower in potential than those over the eye and anterior to it. Behind the eye, that is tailwards, the potentials dropped sharply and no spikes could be recorded at all about 5 to 7 cm. posterior to the eye.

The characteristics of spike potentials recorded from the water surrounding the head region above the eye showed a spike potential of 200–300 μ v, with a duration of 20 milliseconds. Inspection of Figure 2 shows that the spike is triphasic with a shallow positive potential immediately before the spike and a stronger positive potential following it. These characteristics as well as the shape of the spike potential remind us of a nerve action potential in a conducting medium, although both the value of the potential and its duration are unlike either muscle or nerve potentials as recorded from isolated preparations.

It was at once obvious by mere visual inspection that a recurrence of the spike potentials coincided with the respiratory movements of the animal, as revealed by the contraction and relaxation of the gill openings. This became

particularly clear when, at the end of an experiment, the animal became distressed due to the lack of oxygen in the stagnant water and respiratory movements became very slow and often stopped for several seconds. The recurrence of the

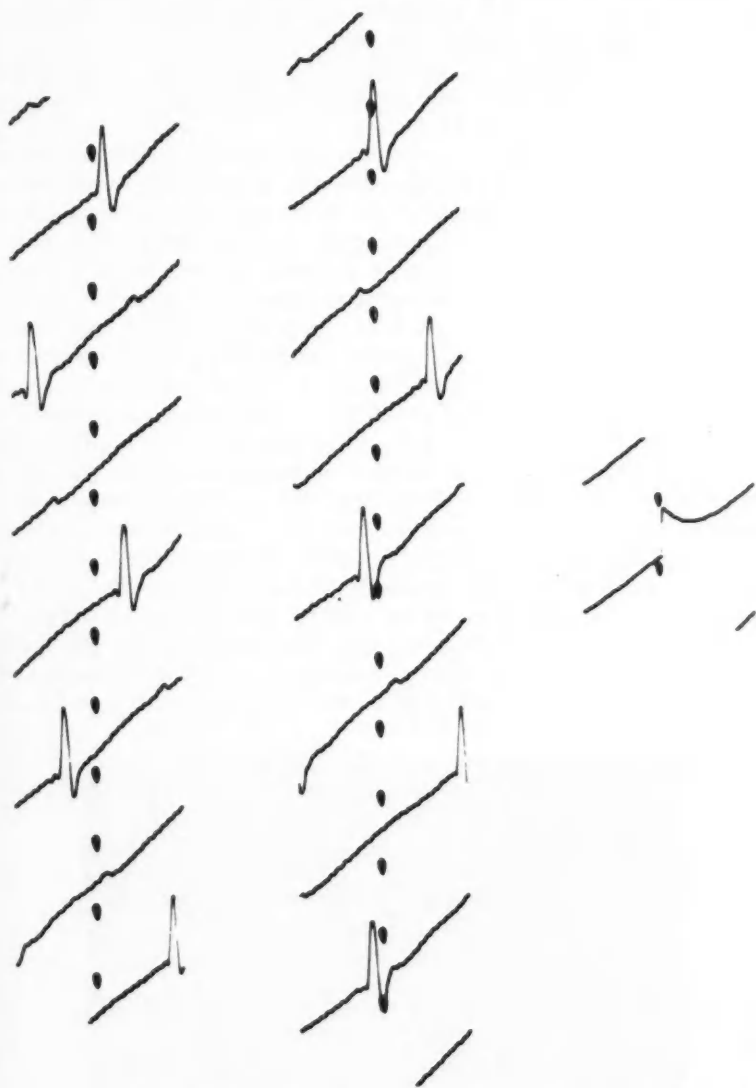


FIG. 3.—Continuous recording of spike potentials in the water surrounding the head region of *Petromyzon marinus*. Recording electrode above the left eye. Time signal $\frac{1}{4}$ sec. Calibration signal at right of Figure is 200 μ v.

spike potentials closely follow these irregular respiratory movements. By using continuously-moving film in the kymograph camera and maintaining the lens shutter open, a continuous recording could be made of the spike potentials under different experimental conditions. The recurrence of the sweeps as well as their width was regulated so as not to lose any part of the recording. Sufficient speed of film motion prevented overlap of spikes. A short length of such continuous recording is represented in Figure 3 where the dots represent a time signal at $\frac{1}{5}$ sec. In a healthy animal in well aerated water the recurrence of the spikes is very regular with an interval of 0.4 sec.

Since there was an apparent synchronization between the respiratory movements and the recurrence of the spike potentials, the possibility presented itself of these potentials being generated by the respiratory centre or muscle contractions related with respiration. As a preliminary step to investigate this possibility, synchronization was checked by means of motion pictures in the manner described under "Methods". The neon bulb was placed in the photographic field of the camera close to the tube in the head region of the animal. The bulb was connected by means of an audio-amplifier and pre-amplifier to the silver wire electrode in the tube in the head region. By proper adjustment the spike potentials were made to light the neon bulb so that intermittent flashes of this bulb represented the occurrence of the spike potentials with negligible delay. The motion picture made of the respiratory movement of the gill openings simultaneously with the flashing of the neon bulb, showed that spike potentials are produced at the onset of the visible respiratory movement of the gill openings. More detail can be observed in Figure 4, which is a still photograph by means of a flash gun as described under "Methods". With open lens shutter in absolute darkness, the flash gun was fired by the amplified spike potential taken from the water surrounding the head of the lamprey. The position of the gill openings in this picture is again that of onset of contraction. A number of pictures were made, all representing the position of the gill opening as shown in Figure 4.

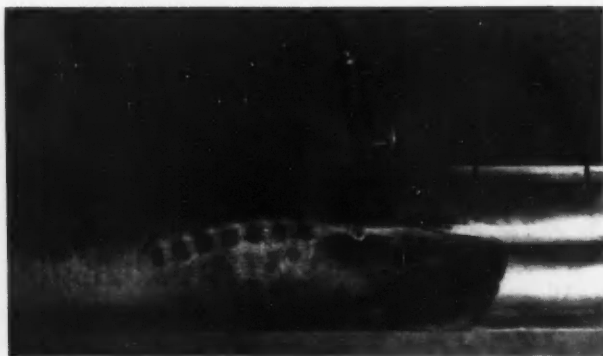


FIG. 4.—Position of gill openings at the moment spikes are recorded from electrode in the water above the left eye. Flash gun was fired by the amplified spike potential.

There is therefore little doubt that the mechanism that produces these spike potentials is synchronized with that of respiration.

Among the many questions to be answered as a result of these unusual observations, two stand out as requiring an urgent answer: 1. What is the source of the spike potential as observed in our experiments? 2. At what point, or points, does it enter the medium surrounding the animal?

To contribute to the answer of the first question, some preliminary experiments were done involving the use of drugs, since considerable progress may be made if it can be ascertained whether these potentials are produced by nervous



FIG. 5.—A. Normal recording from electrode in the water 6 mm. anterior of left eye. B. Same after injection with curare. C. Calibration signal of 100 μ v.

tissue or by muscle. Curare and strychnine were used. Curarized and strychnine-injected animals were used to get some initial information on this point. Injection with strychnine of various concentrations did not in any way alter the characteristics of the spike potentials as observed in controls, whereas on the other hand, the spike potentials produced by curarized animals were considerably lower than those of the controls (Fig. 5). Although these initial experiments seem to indicate that the mechanism generating the potentials observed involves muscle, no final conclusions should be drawn from them. Mutilation experiments involving both the central nervous system, peripheral nerves and respiratory muscles, are now in progress. As yet no results or conclusions can be presented on this part of the work.

One of the most striking of the above observations is that of the obvious high degree of localization of the spike potentials in relation to the animal's body. Measurements made by means of the modified double tube (see "Methods") provide initial information on the shape and dimensions of the electrical field produced by these potentials within the limits of the dimensions of the tubes. It appears from these observations that the electrical field extends far ahead of the animal's head (24 cm.: 126 microvolts). The values of the potential vary with the animal and its condition from as low as 27 microvolts to 126 microvolts under the conditions described. Further experiments are now in progress to study the shape of the electrical field in a container of greater dimensions. Preliminary observations made with an animal in a small-sized aquarium indicate that the electrical field can be recorded at a distance of 62 mm. with spikes of 17 microvolts. The latter value as well as the maximum distance at which potentials could be recorded are provisional since the experimental conditions under which they were made were crude.

Rotation of the measuring electrode around the animal did not indicate, within the dimensions of the tube, an asymmetrical field. Again these preliminary observations are not final, but they do not seem to help at this time in localizing the emission of the potentials from the animal's body. Neither did the application of cocaine on the animal's head provide any clues. The spike potentials were not altered by this treatment.

Light conditions do not effect the spike potentials since they were recorded from animals in complete darkness (see above) and the projection of a strong light on different regions of the head had no noticeable effect. Experiments are now in progress in order to isolate electrically the field produced by the head region from the water behind it.

DISCUSSION

The experimental results reported above leave no doubt as to the emission of bioelectric potentials into the water surrounding the head of the sea lamprey. The synchronization between respiratory movements and the occurrence of these spike potentials is also clearly established. Furthermore the localization of these potentials was shown to be well defined in the head region anterior of the last gill opening. It is obvious from these observations that in the head region of

the sea lamprey one or more "windows" exist which allow for the conduction of the biopotentials into the surrounding medium. In this connection it is of the greatest interest to recall E. A. Stensiö's (1927) paper, on the Downtonian and Devonian Vertebrates of Spitsbergen, in which he describes in great detail so-called "electric nerves" and "electric fields" in cephalaspids, the now extinct ostracoderms to which the sea lampreys are closely related (*l.c.*, pp. 195, 197, 235 and following). Although Stensiö does not exclude the possibility that the organs described by him as electric fields might have been sensory organs with a special function, he finds it very difficult to understand what this special function could have been. He felt inclined to think that in reality they were electric organs and that it is thus obvious that they must have had their superficial parts, which were situated upon the nerve canals, covered by a thin layer of "electric plates".

Another important question is that of the possible function of these electric potentials in the sea lamprey. Their low frequency excludes altogether the possibility of them being useful in orientation of the lamprey on the principle of "radar", as described for bats. On the other hand, it is possible that the lamprey also has sensory organs which detect changes in the electric field it produces, so that any object entering this field and distorting it may be sensed. Once the dimensions and the electric characteristics of the field have been worked out, this possibility must be investigated in detail.

ACKNOWLEDGMENTS

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The Oceanography of Chatham Sound, British Columbia^{1,2,3}

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ABSTRACT

During May–September, 1948, an oceanographic study was made of Chatham Sound, primarily to determine, if possible, whether there was any obvious characteristic of the water in the region which could be correlated with the known migration of salmon to the spawning grounds up the Nass and Skeena Rivers. A detailed analysis of the oceanographic data is presented.

The path taken by the fresh water through the sound is shown to depend on the volume of fresh water being discharged from the rivers. These reach their peak discharge in late May or early June and during this period the amount of fresh water in the sound is three to four times the average. Data obtained at anchor stations occupied for 10 to 40 hours indicate that there is a good correlation between tidal, salinity and temperature cycles.

Dynamic calculations have been made of the velocities, total volume and fresh water transports. During normal river conditions, the agreement with observed velocities, and with fresh water discharges determined from gauge readings, suggests that even in these coastal waters there is an approximate balance between the transverse pressure gradient and the Coriolis force. Stations at the mouth of Portland Inlet exhibit an apparent balance at all times which suggests that transverse inertial and frictional forces are slight compared with the transverse pressure gradient and Coriolis force. Evidence of a variation in geopotential slope associated with the tides is proposed.

The relatively large tidal amplitudes together with the wide and rapid fluctuations in river discharge make it exceedingly difficult to obtain reliable synoptic observations over the entire sound.

INTRODUCTION

Most of the early work in physical oceanography was directed towards the determination of structure and circulation in the open ocean. However in recent years there has been an increasing interest in the oceanography of inshore waters, particularly in bays and estuaries, which from the standpoint of fisheries and industries is of extreme importance.

The history of oceanography since 1938 along the west coast of Canada was reviewed by Tully (1949b). Hutchinson (1928) and Hutchinson and Lucas (1931) have described the general distribution of temperature, salinity, pH, and phytoplankton in the Strait of Georgia. These investigations were initiated in order to determine the extent and influence of the Fraser River on temperature, salinity, currents, and plankton, which are probable factors in determining salmon

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migrations. Carter (1934) has described the characteristics of inlets and fiords in the southern part of the British Columbia coast. Tully (1936) has done considerable work on Nootka Sound and the three inlets directly contiguous with it. In this paper he has discussed the characteristic tidal circulation in the inlets and the possible inverse correlation between temperature and the depth of tidal circulation in those inlets having a threshold. More recently Tully (1949a) has made a quantitative study of the behavior of fresh water entering the sea through Alberni Inlet. In this study he constructed a hydraulic model of the harbour and head of the inlet and from this he has been able to study the effect of river discharge, wind, and tide on the rate of dissipation of fresh water seaward, and to predict the probable extent and degree of pollution of the inlet caused by a proposed pulp mill.

An oceanographic survey of Chatham Sound was carried out by the Pacific Oceanographic Group under the direction of Drs. J. P. Tully and W. M. Cameron during the spring and summer of 1948. The primary purpose of the survey was to determine, if possible, whether there was any obvious characteristic of the water in this region which could be correlated with the known migration of salmon to the spawning grounds up the Nass and Skeena Rivers. To do this requires a knowledge of the physical and chemical properties of the water in the proximity of the rivers and the determination of the extent of the fresh water before it is finally so diluted with sea water that it can no longer be detected.

Cameron (1948a) has discussed briefly the mean distribution of fresh water in Chatham Sound during the periods of maximum river discharge in early June, and the normal river discharge conditions in mid-August, on the basis of the 1948 survey.

The present paper is concerned with a detailed analysis of the data obtained during the 1948 survey.

Cameron (1951) has also made use of some of the data taken at the mouth of Portland Inlet to demonstrate that the mass distribution is in approximate balance with the deflecting force of the earth's rotation. Relative currents calculated under this assumption were found to agree in magnitude and direction with the currents measured during the survey. Fresh water transports, deduced from volume transports, compared favourably with the river discharges. From these calculations it appeared that lateral friction in coastal waters of this type is of secondary importance, and that synoptic surveys may be interpreted in terms of the stationary circulation theory of Sandstrom and Helland-Hansen.

HYDROGRAPHY OF CHATHAM SOUND

Chatham Sound is situated in the northern part of British Columbia and borders on Alaska. It is a semi-enclosed basin with an area of approximately 600 square miles into which the Nass and Skeena Rivers discharge. Several large passages and channels provide communication with the more open waters of Dixon Entrance and Hecate Strait. The largest and deepest of these is the unnamed passage north of Dundas Island, which in this study will be referred to as "Dundas Passage" (Fig. 1). Hudson Bay, Brown, Bell, and Edye Passages open

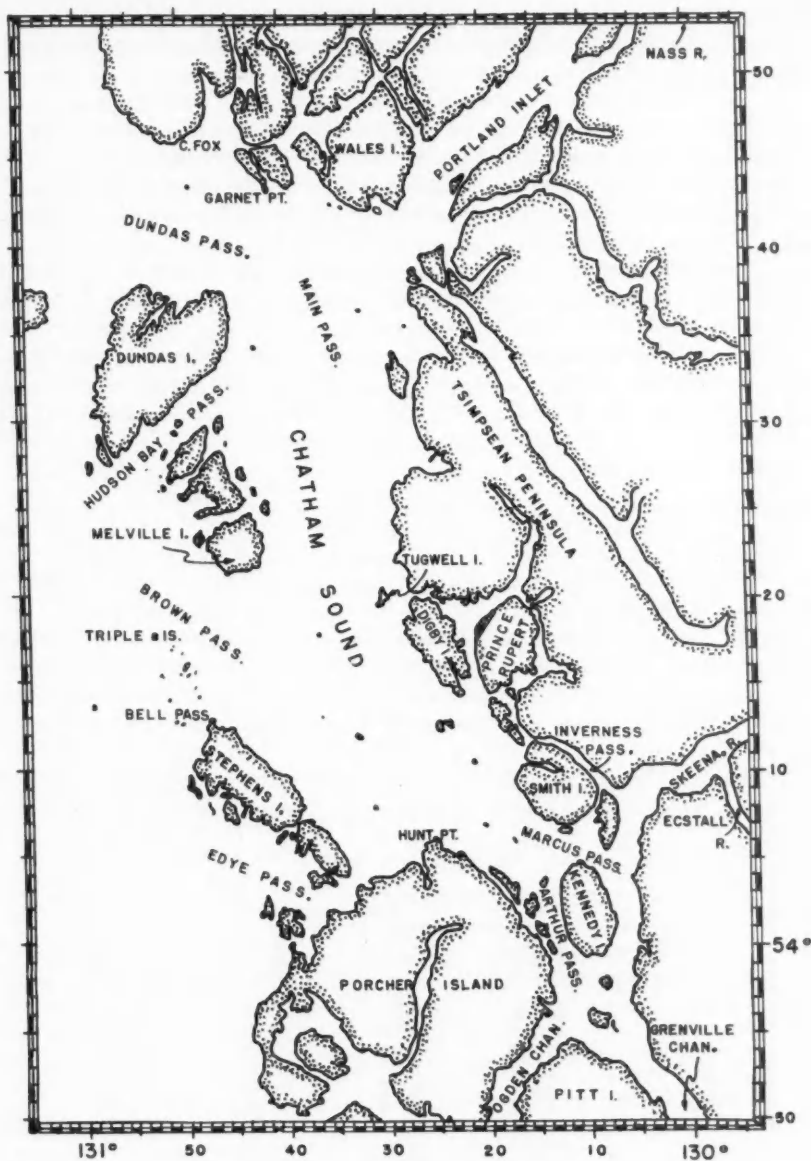


FIG. 1—Chatham Sound, British Columbia.

directly into Dixon Entrance and Hecate Strait, Ogden Channel, between Porcher and Pitt Islands, and Grenville Channel, between Pitt Island and the mainland, provide a more indirect communication with the sea.

The sound contains many rocks, reefs, and shoals, and the depth for the most part is less than 100 fathoms. Only in the northern end are depths greater than 100 fathoms found. Portland Inlet extends inland for some 25 miles from the northeast corner of the sound. There is no sill across the mouth and depths in the inlet are comparable to those in the northern end of the sound (greater than 300 fathoms in some cases).

The sound can be considered as a large reservoir which is supplied with fresh water from the Nass and Skeena Rivers, and with sea water from Dixon Entrance and Hecate Strait. Its average salinity therefore is greater than that of fresh water and less than the normal salinity of the adjacent ocean. Chatham Sound constitutes an estuary in the modern sense of the word but its irregular boundaries and the influx from an additional river make it considerably more complicated than the simple, two-dimensional estuary of which most of the inlets in the coast are examples.

SOME FACTORS INFLUENCING THE CIRCULATION

RIVERS

Fresh water inflow is an essential feature of an estuary and hence a description of the rivers which contribute this fresh water is important.

The Nass and Skeena are the only two important rivers which discharge into Chatham Sound. Skeena River water reaches the sound directly through Inverness and Marcus Passages, and to a lesser extent through Arthur Passage, while Nass River water first discharges into Portland Inlet and thence into Chatham Sound.

These rivers drain a total area of approximately 27,500 square miles of which 7,500 is drained by the Nass and the remaining 20,000 by the Skeena.

TABLE I.—Discharges for the Nass and Skeena Rivers at Aiyansh and Usk respectively.

Month	Mean discharge			
	Nass (1928-48)	Skeena (1927-48)	Nass (1947-48)	Skeena (1947-48)
	<i>Cubic feet per second</i>			
Oct.	30,100	26,830	26,000	26,400
Nov.	19,680	15,140	9,510	14,500
Dec.	9,850	10,170	5,120	8,230
Jan.	7,270	6,930	5,760	8,660
Feb.	6,480	5,560	3,310	6,070
Mar.	4,390	4,840	2,780	3,690
Apr.	15,120	14,420	3,920	6,050
May	44,550	64,240	56,000	127,000
June	71,990	86,470	78,800	103,000
July	59,221	52,890	41,900	42,000
Aug.	44,420	31,170	37,400	28,100
Sept.	30,260	22,690	37,900	37,300
Mean (year)	28,610	28,450	25,700	34,300

The Dominion Water and Power Bureau maintains records of river discharges taken from gauge readings on the Nass River at Aiyansh, 45 miles upstream from the river mouth, and on the Skeena River at Usk, approximately 90 miles upstream from the mouth.

The mean monthly and mean yearly discharges in cubic feet per second for the Nass and Skeena Rivers have been tabulated and are presented in Table I. This table indicates that as a rule the mean yearly discharges for these rivers are very nearly equal. However, it should be pointed out that these figures are only approximate, since the records, which were commenced in 1927 for the Skeena and in 1928 for the Nass, contain several gaps. The most notable are for the period 1932-36 when the Skeena was not gauged, and similarly for several

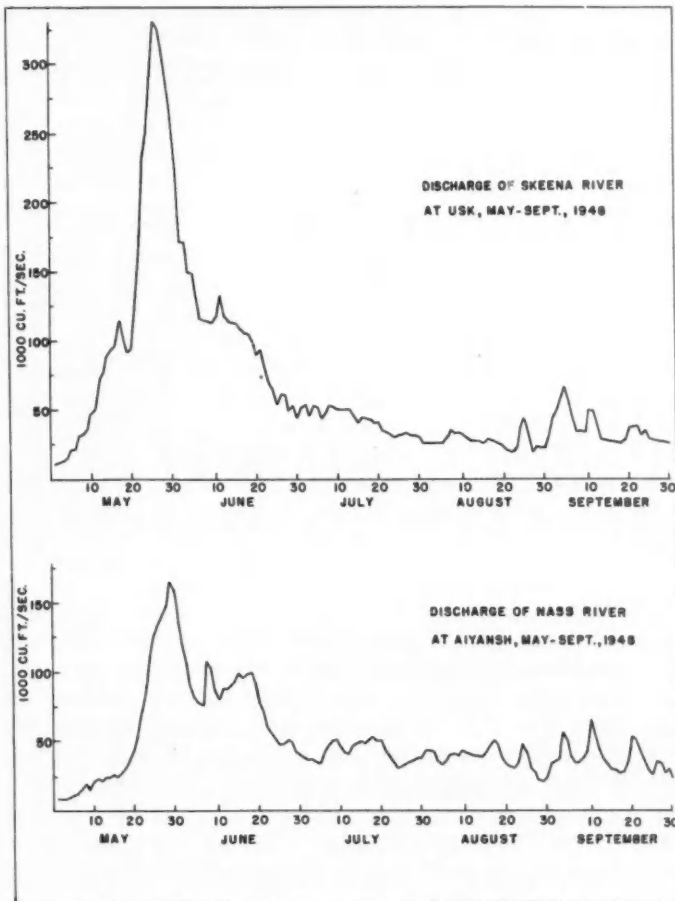


FIG. 2—Discharge of Nass and Skeena Rivers, May–September, 1948.

years no figures are available for the Nass during the months of December, January, February and March. These rivers reach a mean monthly maximum in June of three to four times their yearly mean, and a minimum in March of less than one-fifth their mean. The Skeena however has the wider fluctuations.

Table I also indicates that for the year 1947-48 the Skeena discharge was 20% greater than average while the Nass discharge was about 10% lower than its average. However, the total discharge for both rivers together was only slightly higher than the average.

The maximum discharge for the Skeena was recorded on May 28, 1948, when it reached a figure of 330,000 cubic feet per second. This was more than three times the average peak and broke all previous records. The maximum discharge of the Nass was likewise abnormally high, although it was not a record. Daily discharges of the Nass and Skeena Rivers from May to September, 1948, are plotted in Fig. 2.

TIDES

The tides in Chatham Sound are classed as semi-diurnal, mixed; there being two high waters and two low waters each day, no two of which are equal in height.

Tide tables published by the Hydrographic and Map Service of Canada give the time and height of each high and low water at Prince Rupert. Time and mean height differences of high and low water for various parts of the sound are given with reference to Prince Rupert Harbour. However, time differences are only of the order of a few minutes and height differences are less than 2 feet.

In this report the four points on the tidal cycle for which times and heights are recorded will be referred to as higher low water (HLW), lower high water (LHW), lower low water (LLW), and higher high water (HHW).

The tidal range in the sound is relatively large having a mean value of about 20 feet. As a result of this large amplitude, large volumes of water must move into and out of the sound resulting in tidal currents of the order of 1 to 2 knots in the various passages.

METEOROLOGY

Twice-daily observations of cloud cover, wind speed and direction are recorded at Triple Island by the Meteorological Service. During the period of the 1948 survey the average direction of the wind lay between north and west, and the average speed was 10 to 15 miles per hour. Detailed meteorological data are also recorded at Prince Rupert, and in addition to this, observations of weather conditions were made at each station during the survey.

COLLECTION OF DATA

The oceanographic research vessel H.M.C.S. *Ehkoli* was used to make this survey. Observations were commenced on May 19 and continued to September 10, 1948. Initially a network of stations was established in the sound, but ad-

ditional stations were incorporated, some changed, and some dropped, during the course of the survey as more pertinent locations were established. One survey of parts of Dixon Entrance, Hecate Strait, and the entrance of two of the Alaskan passages in the vicinity of Chatham Sound was made to determine the general oceanographic feature of the area. Occasionally, more intensive investigations were made of small areas such as the immediate approaches to the Skeena.

Salinity observations were made by titrating samples of water drawn from selected depths, using Ekman water-sampling bottles. Observations were made for the most part at depths of 0, 3, 6, 12, 18, 24, 30, 36, 48, 60, and 90 feet. However, at certain stations observations were made to a depth of only 60 feet, while at others the observations extended to 150 feet. Following the normal oceanographic procedure, each geographical position at which observations were made will be referred to as a "station", and each lowering of the bottles or instruments at a station, as a "cast". Temperature measurements were obtained largely with a bathythermograph, although some temperatures were recorded using Richter and Wiese reversing thermometers primarily for calibration of the bathythermographs. Approximately 1000 bathythermograph casts were made.

Approximately 6000 samples of water were obtained and titrated aboard ship to determine the salinity. The Mohr method of analysis was employed to obtain the chlorosity of the sample, salinity being determined from conversion tables.

Six anchor stations were occupied for periods varying from 10 to 40 hours. Temperature and salinity observations of the water column were made for all stations at intervals of 1 to 2 hours, and at three of them current observations were made at various depths between the surface and 60 feet, using a current drag.

METHODS OF ANALYSIS OF DATA

For each station, salinities, temperatures, and in some cases densities, were plotted against depth. Temperature-salinity plots were also made for each station.

At any particular time, the horizontal variation of temperature over the sound was found to be slight and hence little use was made of temperature-topography plots. Cross-sections of temperature might have been useful, but very few were available owing to the layout of the stations. Temperature observations, however, have been used indirectly in calculating densities and dynamic heights.

T-S curves were plotted for each station, but did not prove to be of primary value in this problem, because, as mentioned previously, temperature variations were small and their significance not apparent.

In this study it was found convenient to introduce the expression, "fresh water concentration" (c), to represent the percentage of fresh water that a given sample of water contains. The value of c of course depends on the value chosen for the salinity of undiluted sea water. This salinity which has been chosen arbitrarily as 31.30‰ results in causing c to be negative in a few instances. Since emphasis is placed on relative differences, this is not considered to be a serious deficiency.

The relationship expressing the concentration of fresh water c in water of salinity S_z at any depth (z) is given by:

$$c_z = 1 - \frac{S_z}{31.30} \quad (1)$$

Thus water with a salinity of 10‰ has a fresh water concentration of 0.68, i.e. it contains 68% fresh water and 32% sea water.

The mean concentration of fresh water (C) in any depth interval can then be evaluated from the relation:

$$C = \frac{1}{z} \int_{-z}^0 c \cdot dz \quad (2)$$

(vertical axis is taken as positive upward)

C was evaluated at each station for the upper 60 feet. The integration was performed by the use of a planimeter to measure the area between the salinity-depth curve and the 31.30‰ line.

Plots of C have been used extensively in this study because they seemed to give a good indication of the mean flow of fresh water seaward, and appeared to offer a distinct advantage over plots of salinity. Very often horizontal plots of salinity at some particular depth contained many tongues of high or low salinity water, while a plot a few feet deeper contained few or no tongues. These local invasions of high or low salinity water, which contributed little to the mean flow, tended to be "smoothed out" in C plots.

On the assumption of gradient flow, surface velocities and volume transports (using the method demonstrated by Jakhelln, 1936), normal to the line joining pairs of stations, were calculated for several sections in the sound.

The horizontal fresh water transport through an elemental area may be written as:

$$f.w.t. = v \cdot c \cdot dx \cdot dz \quad (3)$$

where c = concentration of fresh water passing through the area $dx \cdot dz$, and v = velocity at right angles to the area.

Integrating this gives:

$$F.W.T. = \iint v \cdot c \cdot dx \cdot dz \quad (4)$$

or,

$$F.W.T. = \frac{10}{\lambda} \int c \cdot \delta(\Delta D) \cdot dz \quad (5)$$

where λ = Coriolis parameter and ΔD = dynamic height anomaly.

However, this equation cannot be integrated as simply as for volume transports, unless a relationship between c and $\delta(\Delta D)$ can be established. It can, however, be integrated by assuming that the gradient of fresh water concentration at each level, between two stations, is uniform. At each level p , this requires the use of the arithmetical mean fresh water concentration \bar{c} :

$$\bar{c} = \frac{C_{pA} + C_{pB}}{2} \quad (6)$$

c is then substituted for c in equation (5) and the integration performed in the usual manner, giving, between two stations A and B:

$$F.W.T. = \frac{10}{\lambda} \bar{c}(\Delta D_B - \Delta D_A) dz. \quad (7)$$

Fresh water transports determined for various sections can be compared with one another and with the known inflow of fresh water from the Nass and Skeena Rivers.

AVERAGE FRESH WATER DISTRIBUTION AND SALINITY PATTERN

The average fresh water distribution and salinity observed in Chatham Sound during normal river conditions will be discussed first, so that the patterns and distributions observed at other times may be compared with them.

For the month of August both the Nass and Skeena Rivers have discharges very nearly equal to their yearly mean. A network of stations in the sound was occupied during the period from August 10 to 19, 1948. For the first 4 days the southern half of the network was occupied, once each day, the timing of the observations being so arranged that at the end of 4 days each station had been occupied at four different stages of the tide, i.e. LHW, HHW, HLW, and LLW. In order to present an average picture the observations of each station were averaged. Similarly, observations for the northern half of the network were taken during August 16-19. The average distribution of fresh water is presented in Fig. 3. The concentration in the sound was between 1.1 and 9.9%, the highest value being observed at station 29, located just south of Garnet Point (Fig. 4), and the lowest at station 47, located near Triple Island. A secondary maximum of 8.8% was observed at station 41, off Inverness Passage.

Due to the earth's rotation, the flow of fresh water into the sound from the Nass and Skeena Rivers, at normal levels, shows the tendency to turn to the right which is common to all river outflows in the Northern Hemisphere. From the pattern illustrated, it is evident that very little Skeena River water flows out through Brown, Bell, or Edye Passages. Instead, the net seaward flow of Skeena River water takes place up the east side along the shore of Digby Island and continues northward past Tugwell Island and along the mainland coast of the Tsimpsean Peninsula.

The Nass River water tends to be concentrated along the north shore of the sound, moving out past Wales Island, through Dundas Passage, and finally into Dixon Entrance.

In Fig. 5 the average surface salinity pattern during the same period is presented. Salinity varied from less than 24‰ at station 42, located southwest of Inverness Passage, to greater than 30‰ at station 47. While this pattern indicates the same general flow in the southern end of the sound as the plot of fresh water concentration, the isohalines are more wavelike in the northern end and suggest that there is some flow of Nass water at the surface toward the south along the eastern shore of Dundas Island. However, examination of the salinity pattern at 6 feet and at deeper levels indicates that this southward tendency is confined to

the upper few feet. The extension of the tongue towards Hudson Bay Passage suggests some seaward movement of fresh water through this passage. This suggestion is also indicated in the fresh water concentration plot.

It would seem then, that although a thin surface layer of Nass water extends southward, most of the fresh water in the southern and central part of Chatham Sound is derived from the Skeena River.

One concludes therefore, that during normal river conditions, there is little

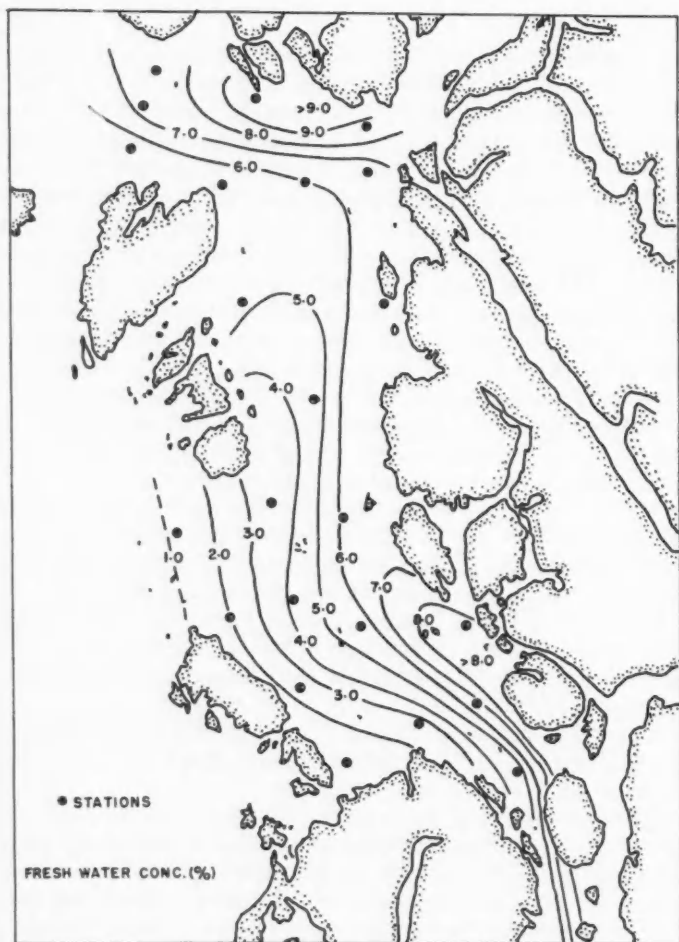


FIG. 3—Percentage fresh water in upper 60 feet during normal river conditions, August 10-19, 1948.

seaward movement of fresh water through Brown, Bell, and Edye Passages or through Ogden and Grenville Channels. Most of the Skeena River water moves northward along the Tsimpsean Peninsula, merges with the Nass River water, and finally the greater part leaves Chatham Sound through Dundas Passage, with possibly a small amount passing through Hudson Bay Passage.

SURVEYS

The surveys of Chatham Sound will now be discussed in chronological order.

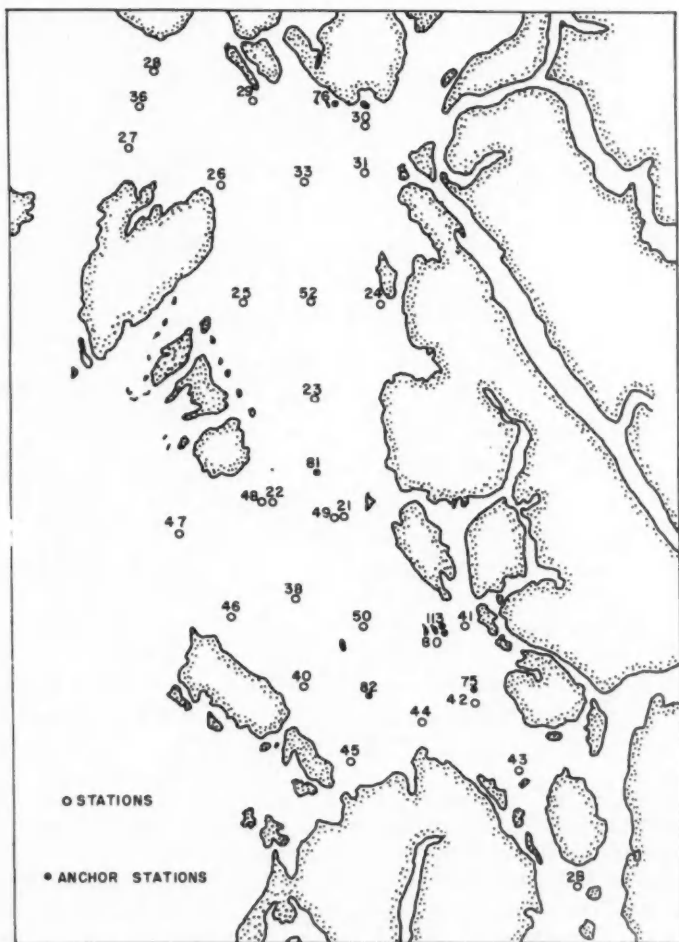


FIG. 4—Locations and numbers of stations most frequently occupied during survey, May–September, 1948.

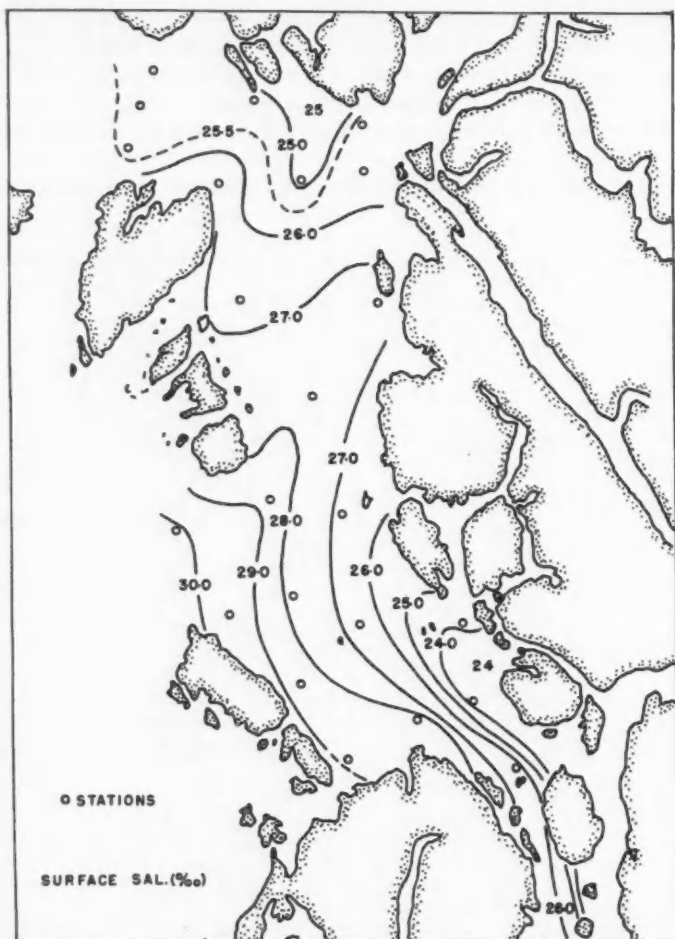


FIG. 5—Surface salinity pattern (‰) during normal river conditions, August 10-19, 1948.

(1) MAY 19-MAY 21

This was a general survey of the sound in which most stations were occupied twice—once during the flood tide and once during the ebb.

Surface salinities, salinities at 6 feet, and fresh water concentrations have been plotted. Figure 6 illustrates the pattern of fresh water concentration and salinity at 6 feet for the flood and ebb phases of the tide. The patterns observed are very similar to those illustrated for normal river discharge conditions.

(i) *Flood*—Fresh water concentration ranged from less than -1.0% at the

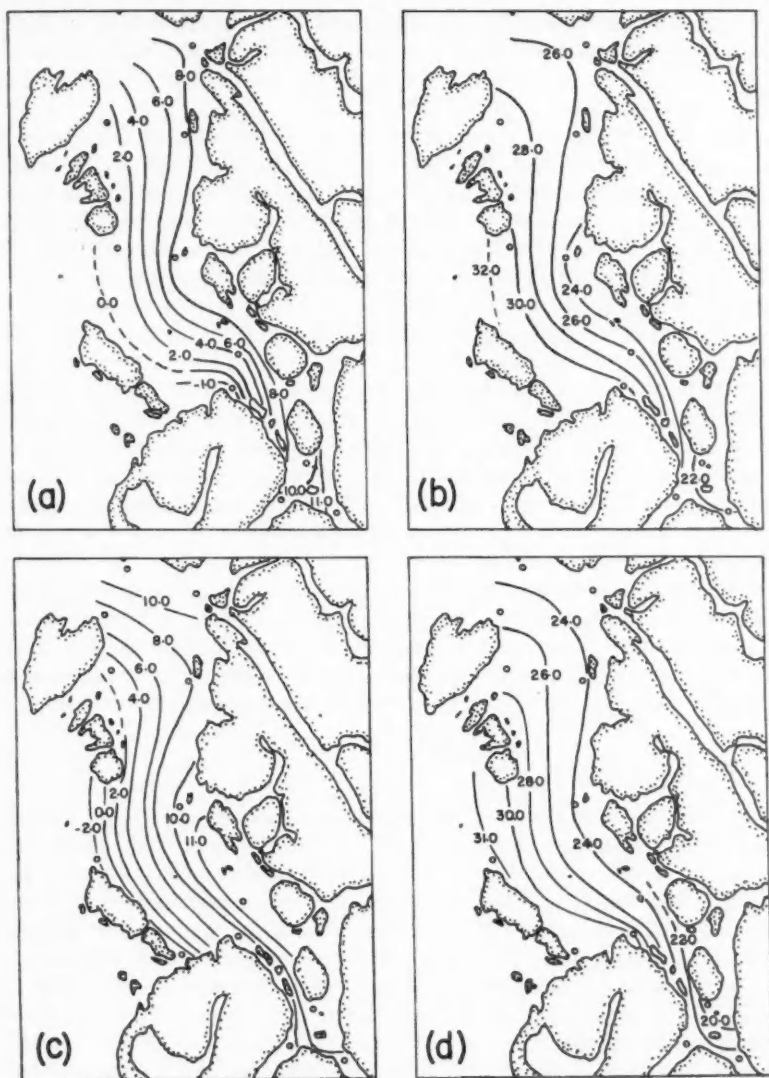


FIG. 6—Fresh water concentration (%), and salinity (‰) patterns at 6 feet, May 19–21, 1948.

- (a) Fresh water concentration, flood tide.
- (b) Salinity, flood tide.
- (c) Fresh water concentration, ebb tide.
- (d) Salinity, ebb tide.

station near Hunt Point to greater than 11.0‰ at the northern end of Grenville Channel. The salinity plots agreed very closely with those of fresh water distribution, the salinity varying from 22‰ at the northern end of Grenville Channel to 31‰ near Hunt Point.

(ii) *Ebb*—While the effect of tide on the distribution of salinity or fresh water does not reveal itself very markedly in these plots, still a difference can be seen by noting the shift in the 8‰ *C* line. The most marked shift was in the southern end of the sound, where the 8‰ isopleth moved about 5 miles southward during the ebb tide, and replaced the 0‰ isopleth. In the northern part of the sound the 8‰ isopleth also shifted a few miles further off Portland Inlet and was replaced by the 10‰ isopleth. The change in salinity pattern between ebb and flood tide was of the same order of magnitude as for the fresh water concentration.

Ideally, if there was no net flow of water in the sound over a tidal cycle, then observations taken midway on the flood and ebb tide would reveal the same distribution of fresh water. The fact that this is not observed indicates a net flow during a tidal cycle. There must be a net seaward movement of fresh water, equal to the river discharge, otherwise accumulation would result. However the small variation in salinity and fresh water concentration, near Edye Passage, suggests a net northerly tidal set through it.

The slightly higher concentration of fresh water in the southern part of the sound, compared with the normal, was due to the increase in Skeena River discharge, which had been increasing steadily from about May 10 (Fig. 2). The Nass did not show a comparable increase in discharge. These patterns then, correspond closely to the average conditions shown previously for the mid-August survey.

(2) MAY 25–MAY 28

The stations occupied were only those in the southern end of the sound. However the results indicate a considerable change from the May 19–21 survey.

In Fig. 7, the mean fresh water concentration and mean salinity at 6 feet are presented. The 8‰ *C* line stretched in a more nearly east–west direction, compared with the north–south direction on May 19–21, and even extended outside Melville Island. The 14‰ *C* line was almost coincident with the position of the 8‰ line on May 19–21. The mean fresh water concentration varied from less than 2% in Bell Passage to greater than 21% just seaward of Inverness Passage.

The salinity pattern at 6 feet was very similar to the fresh water concentration plot. However, the surface salinity was quite different, especially in the region just north of Edye Passage and along the northeast shore of Stephens Island. A very thin layer of water of relatively low salinity had evidently spread out over the area from the Skeena.

Tidal effects were almost completely masked by the effect of the large increase in river discharge. However, the station near Hunt Point still showed a variation in fresh water concentration of about 1.5% from high to low water (increasing during the ebb).

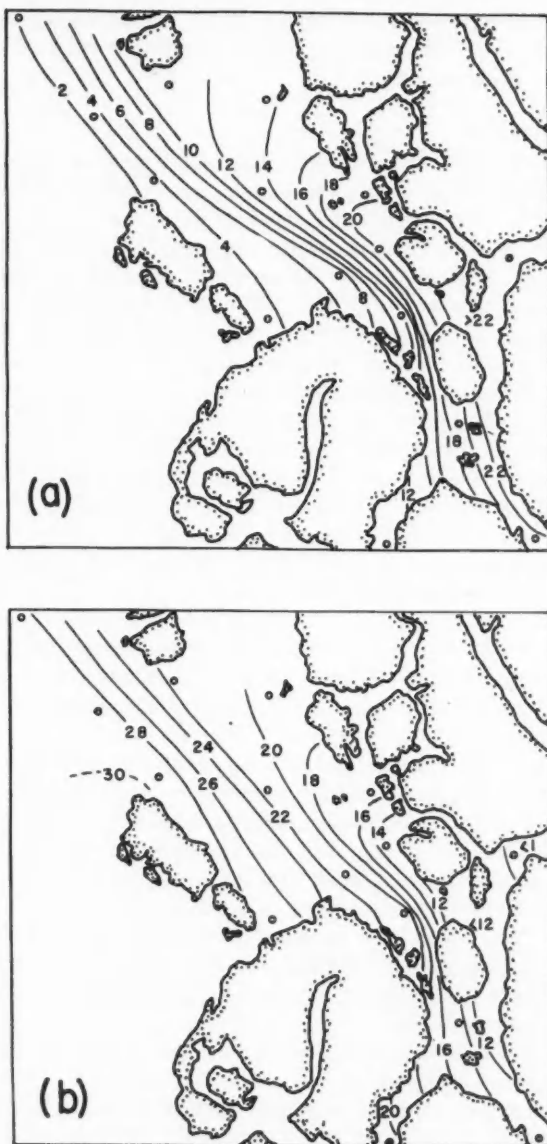


FIG. 7—Fresh water concentration (%), and average salinity pattern at 6 feet, May 25–28, 1948.

- (a) Fresh water concentration.
(b) Salinity.

This set of observations evidently represents a transient state in which the circulation in the sound was changing from normal conditions to that corresponding to maximum fresh water discharge.

(3) JUNE 1-JUNE 4

In this period the northern part of the sound was surveyed. Each station was occupied four times during the survey—once each day, and at different stages of the tide. The mean distribution of fresh water is presented in Fig. 8(a). The highest concentration, 22.6%, was found at station 29; the lowest, 9.8%, at station 27 located just off the northwest coast of Dundas Island. This change represents an increase in fresh water to more than double that during normal conditions. The mean surface salinity is presented in Fig. 8(b). Its pattern is similar to the fresh water concentration plot, the range of values being from less than 11‰ at station 29 to 21‰ at station 27.

The fact that the lines of constant C still portrayed the same general pattern as under normal conditions, does not necessarily imply that all the fresh water from the Nass was moving seaward through Dundas Passage. Although the bulk of the fresh water was moving seaward through this passage, the increase in fresh water discharge resulted in increased flow across the isopleths, and hence it is probable that there was considerable movement toward the south and west, especially in a thin surface layer.

Plots of fresh water concentration were made for each phase of the tide (LHW, HHW, HLW, LLW) and were found to exhibit patterns quite different from the mean. Large but inconsistent variations were noted in each. It appears that during this period observations taken at the same phase of tide but on different days could not be used to give a synoptic picture.

Plots of fresh water concentration were made for each day regardless of tide. It was evident that the resulting patterns were more reasonable than those plotted using only data taken in the same tidal phase but on different days. In these plots (Fig. 8(c), (d), (e), (f)), the highest fresh water concentration of 28.6% occurred on June 1 at station 29. This maximum is associated with the peak discharge of the Nass which occurred 3 to 4 days earlier.

The June 2 plot indicates a decrease in the maximum C to 25.2%. It also shows a southward extension of the isopleths into the central part of the sound which indicates that this large cell of relatively fresh water had a southward as well as a westward component.

On June 3 there was a further decrease in fresh water concentration and a more marked southward movement.

By June 4 this large cell of exceedingly high fresh water concentration had almost disappeared.

It would appear that this large body of brackish water, observed on June 1, had moved part way out into the sound due to the hydraulic head established in Portland Inlet by the increase in river discharge. Since the rate of drop in river discharge was about equal to the rate of rise, then this resulted in a body of water of very high fresh water concentration being partially isolated. The

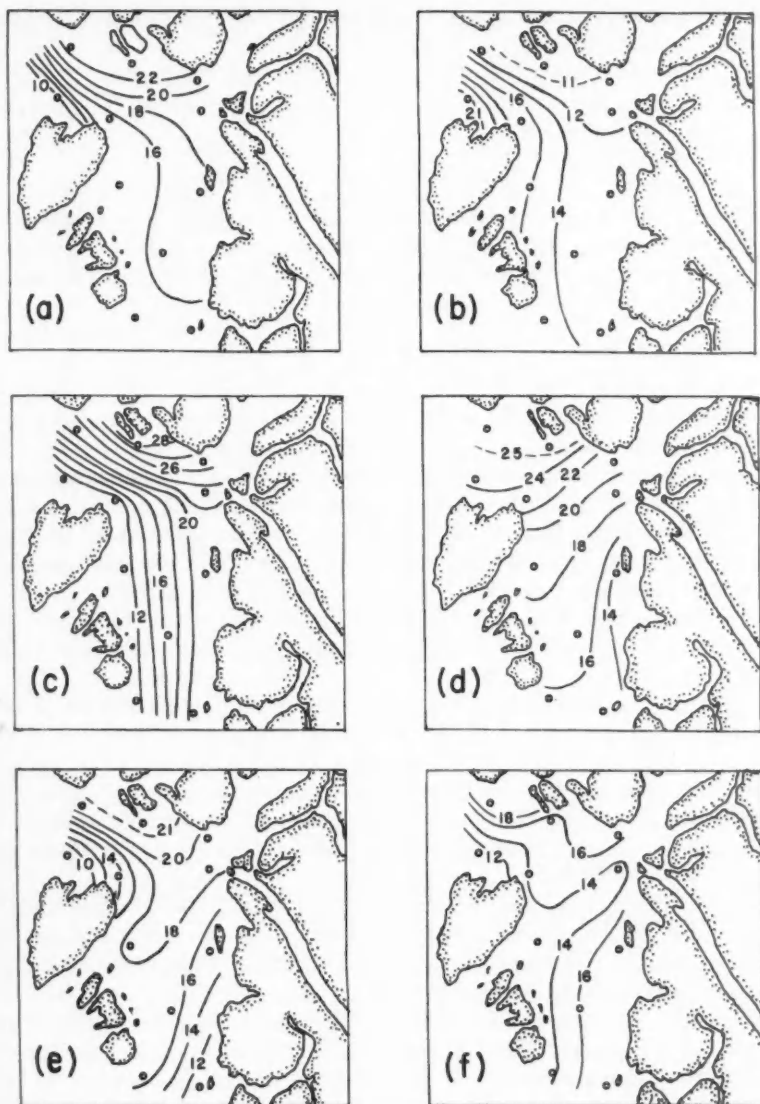


FIG. 8—Fresh water concentration (%), and surface salinity, June 1-4, 1948.

- (a) Average fresh water concentration, June 1-4.
- (b) Average salinity, June 1-4.
- (c) Fresh water concentration, June 1.
- (d) Fresh water concentration, June 2.
- (e) Fresh water concentration, June 3.
- (f) Fresh water concentration, June 4.

dispersal and removal of this water resulted from energy supplied from any one or all of the following sources:

- (a) Kinetic energy which this body had at the time of isolation.
- (b) Energy possessed by virtue of its higher potential than the surrounding more saline water.
- (c) Tidal energy.
- (d) Wind.

In this case (a) and (b) will result in cross-isobaric flow which will be directed in the main westward through Dundas Passage and to a lesser extent southward into the central part of the sound. Undoubtedly (c) and (d) will play their part also, but to what extent is not known.

(4) JUNE 8-JUNE 18

From June 8 to 11 the northern part of the sound was surveyed, the stations being occupied once each day at different tidal phases. Similarly, during June 14, 15, 17 and 18, the southern part of the sound was surveyed.

The observations at each station were averaged to a mean picture corresponding to maximum fresh water discharge conditions. (At the gauge stations the river flows had actually passed their peaks but were still about four times their mean. In the sound the effect of the maximum flow was still being felt.) The mean distribution of fresh water presented in Fig. 9 indicates that the concentration varied from 5.2% at station 47 to 18.1% at station 41. A secondary maximum of 16.9% was located at station 26, off the northeast corner of Dundas Island.

The sound had for the most part a fresh water concentration of 10 to 15% as compared with the normal conditions of 1 to 6%. Considerable quantities of fresh water were reaching Hecate Strait and Dixon Entrance through all the passages. Nass water appears to have extended southward as far as Melville Island, which suggests that there was little Skeena water reaching the northern part of the sound. However, Dundas Passage appears to be still transporting seaward more fresh water than any other passage.

Plots of fresh water concentration and salinity distribution were made for each stage of the tide. However, as mentioned previously, it was apparent that the large increase and unsteadiness of river discharge completely masked any tidal effect which might have been present.

Plots of C for each day were drawn and found to have a measure of continuity from day to day. They are presented in Fig. 10(a), (b), (c), and (d).

On June 8 the minimum, 6.9%, was at station 29, and the maximum, 17.8%, was at station 25, near Hudson Bay Passage. A tide line was observed to extend northeast from Dundas Island towards Wales Island. This intruding, more saline water apparently pinched off relatively fresh water located along the north shore of Dundas Island. The presence of this tide line, and the displacement of the maximum fresh water concentration southward, were quite possibly due to wind effects. During June 7 and 8, northwest winds with speeds of 25 to 30 miles per hour were recorded at Triple Island. It is probable then, that these winds

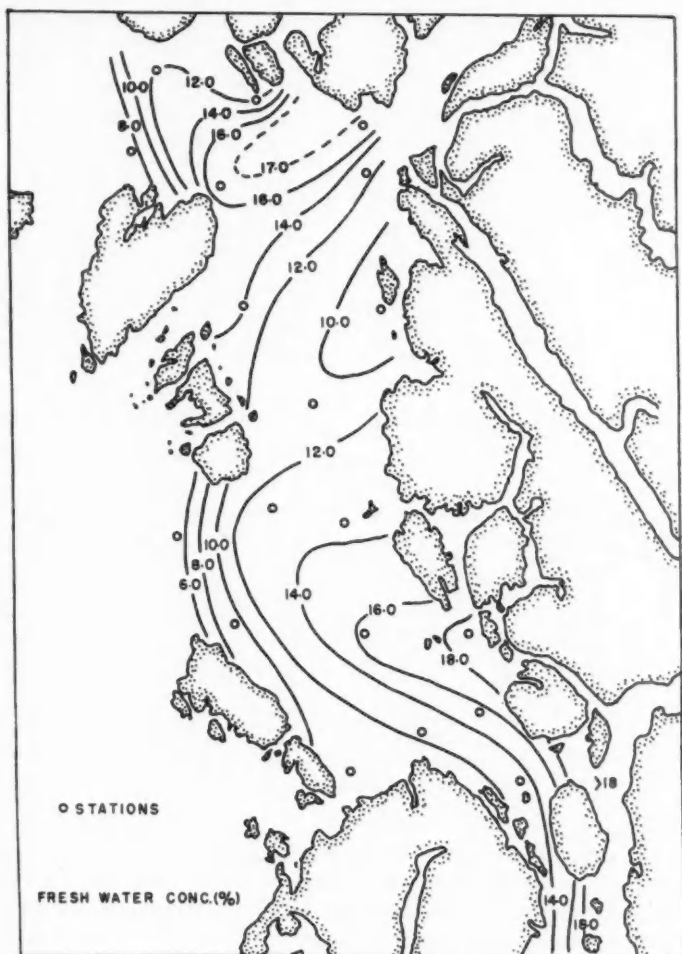


FIG. 9—Fresh water concentration (%) in upper 60 feet during freshet conditions, June 8-18, 1948.

were tending to force more saline water into Dundas Passage and consequently forcing to the south the fresh water flowing out from Portland Inlet.

On June 9 the minimum C , 3.8%, was at station 24; the maximum, 16.6%, at station 26. This indicates an apparent return northward of the cell of maximum fresh water concentration. This, in part, may have been due to the gradual subsidence of the wind and the circulation returning to normal.

The June 10 plot indicates an increase in fresh water concentration to a

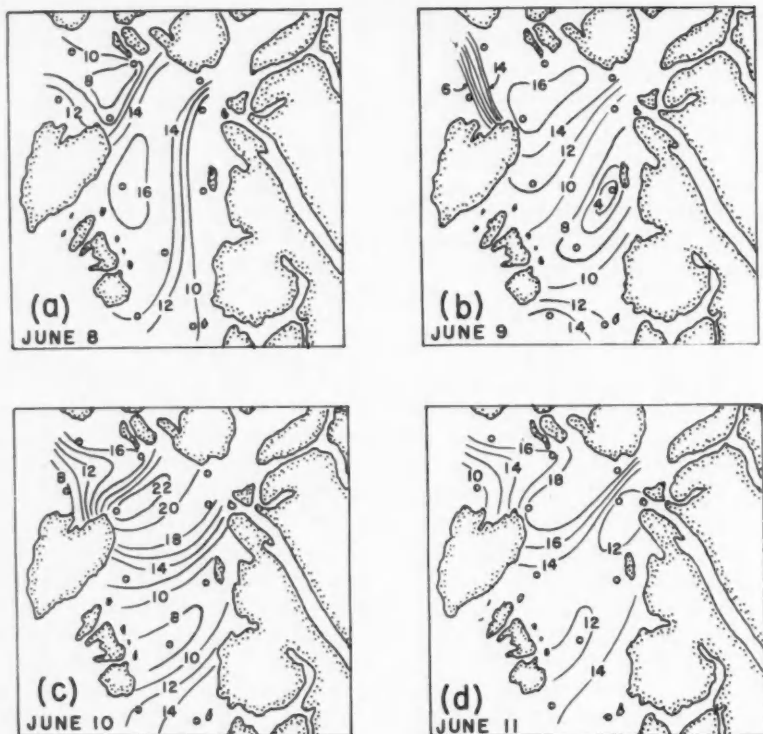


FIG. 10—Fresh water concentration (%), June 8–11, 1948.

maximum of 22.1% at station 26. This increase can be correlated with the increase in discharge of the Nass River of 44%, which occurred between June 7 and 8.

On June 11 the maximum C of 18.6% was located at station 26, which is in reasonable agreement with the drop in river discharge between June 8 and 9.

Fresh water concentrations for June 14, 15, 17, and 18 are plotted in Fig. 11(a), (b), (c), and (d) respectively.

On June 14, a minimum of 5.6% was observed at station 47, located near Triple Island, and a maximum of 15.9% at station 50, located in the south-central part of the sound. There is evidence of a considerable flow of fresh water through Edye, Bell, and Brown Passages.

On June 15 the minimum of 5.3% was still at station 47 but the maximum of 17.4% was at station 41.

The distribution on June 17 indicates a decrease in the minimum at station 47, to 2.6%, while the maximum at station 41 has increased to 23%. It is quite possible that an even higher value was reached on June 16. This increase may have been due in part to the increase in Skeena River discharge of approximately

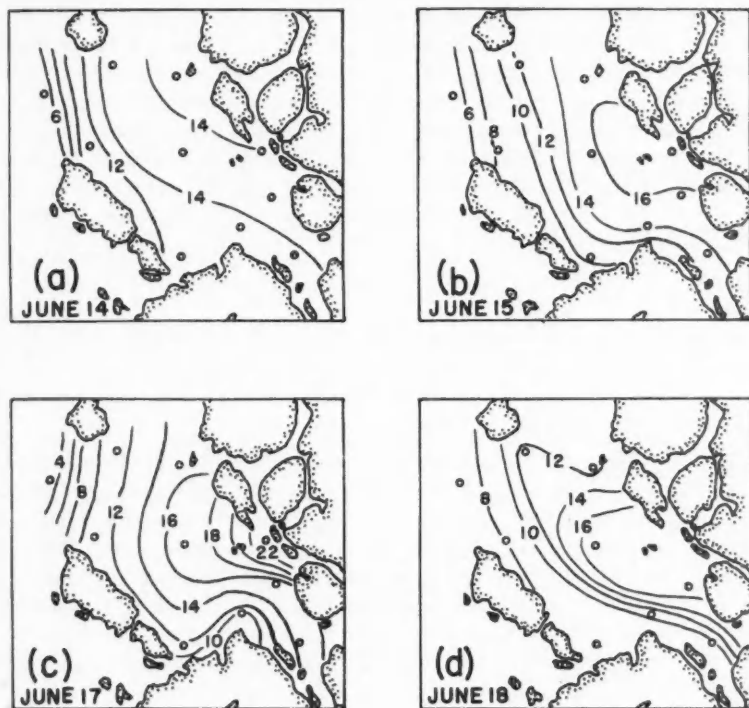


FIG. 11—Fresh water concentration (%), June 14–18, 1948.

12% between June 10 and 11. However, the apparent increase may also have been due partly to the effect of the tide. Station 47 was occupied near high water, whereas station 41 was occupied near low water; consequently minimum and maximum values respectively, due to tidal effects, would be expected at these stations. Since these are relatively shallow areas, it would be expected that a larger variation in salinity would occur between high and low water than in an area where depths are greater and horizontal salinity gradients less.

The plot of June 18 indicates an increase of the minimum C to 7.1% and a decrease of the maximum to 16.9%. This decrease of the maximum may, as on the previous day, have been due partly to tidal effects, or it may have been due to the decrease in river discharge. In this instance, tidal effects seem more likely to have given rise to the apparently large changes in distribution of fresh water in the sound.

From the plots presented for the period June 8 to 18 the large daily variations are obvious. These variations were due principally to the large and unsteady fresh water discharge. The observations in the southern part of the sound, however, indicate that some tidal effects were appearing.

(5) JUNE 21-JUNE 26

During this period a general survey was made of parts of Hecate Strait, Dixon Entrance, and the entrance to two of the passages in southeastern Alaska. From this survey it appears that little of the fresh water discharged from Chatham Sound was reaching the Pacific Ocean through Hecate Strait. Fresh water concentrations as high as 9.2% were observed some 50 miles northwest of Cape Fox, and in Dixon Entrance concentrations of approximately 7% were observed some 35 miles west of Dundas Island. Concentrations west of Triple Island decreased to less than 1% within 10 miles.

(6) JULY

During July 2 to 7 inclusively, and July 22 and 23, four anchor stations were occupied. The results of these will be presented and discussed later.

(7) AUGUST 3-AUGUST 5

During this period stations in the north and central part of the sound were occupied, some three times, some twice and some only once. The data from the stations occupied more than once were averaged. The fresh water distribution for this period is presented in Fig. 12(d). The concentration varied from 3.5% at station 27 to 18% at the station just south of Cape Fox, while a secondary maximum of 16.6% was observed at station 30, located just south of Wales Island. The high concentration near Cape Fox suggests one of two possibilities:

- (a) Relatively fresh water was entering the area through passages north of the sound,
- or (b) A cell of relatively fresh water was moving out of the area.

It is instructive to compare the distribution of fresh water on August 3 with that on August 5 (Fig. 12(a) and (c) respectively). On August 3, *C* varied from 7.8% at station 31 to 17.0% at station 33 and on August 5 it varied from 6.0% at stations 21 and 22 to 18.0% at station 31. The change in pattern was undoubtedly due largely to two factors:

- (i) Differences in tidal phases,
- (ii) Variations in fresh water discharge.

Comparison of the two sets of data between Melville and Tugwell Islands indicates that there was a decrease in fresh water concentration from August 3 to 5. However, both sets of data were taken on the same tidal phase. This suggests that (ii) was the predominant factor here. In the area southwest of Digby Island an even larger decrease in fresh water concentration is noted. The observations on August 3 were made midway on the flooding tide, while on August 5 observations were made immediately after high water. This suggests that the observed change was possibly the result of both (i) and (ii).

Station 31, located at the mouth of Portland Inlet, was occupied near low water both times, but the concentration was 18% on August 5 compared with 7.8% on August 3 which suggests that (ii) was the important factor.

During the few days prior to this period of August 3-5 the Nass discharge

was increasing while that of the Skeena was decreasing. This fact supports the suggestion that the large observed fluctuations of fresh water in the sound were mainly due to variations in river discharge.

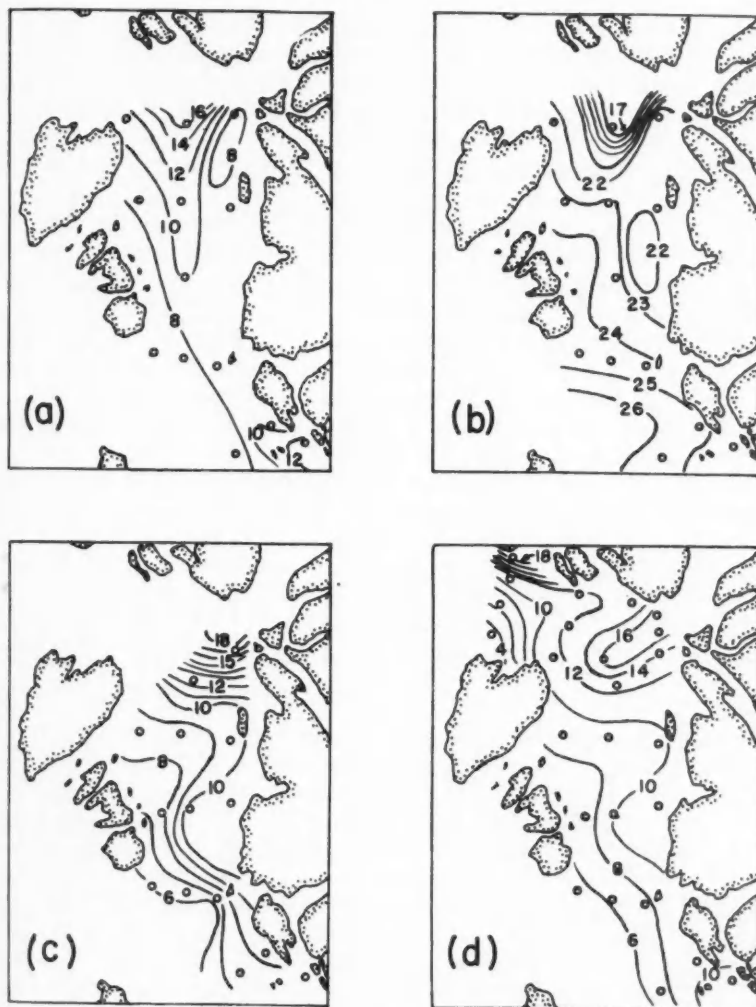


FIG. 12—Fresh water concentration (%) and surface salinity, August 3-5, 1948.

- (a) Fresh water concentration, August 3.
- (b) Surface salinity, August 3.
- (c) Fresh water concentration, August 5.
- (d) Fresh water concentration, August 3-5.

(8) AUGUST 10-AUGUST 19

The mean distributions of fresh water and surface salinity during this period have been shown in Figs. 3 and 5. Here, as in the June 8-18 survey, plots were made for each tidal phase. Although the fresh water discharged into the sound from day to day remained relatively constant, the time interval over which the survey was made appears too long to allow a synoptic picture to be drawn. Evidence of this occurs upon examination of a station located near Tugwell Island which was occupied during both parts of the survey. It illustrates that the variation in fresh water concentration for similar stages of the tide, but on different days, was greater than the maximum variation between high and low water.

Plots of fresh water concentration have been made for each day regardless of tide. The patterns in the southern half varied only slightly from the average,

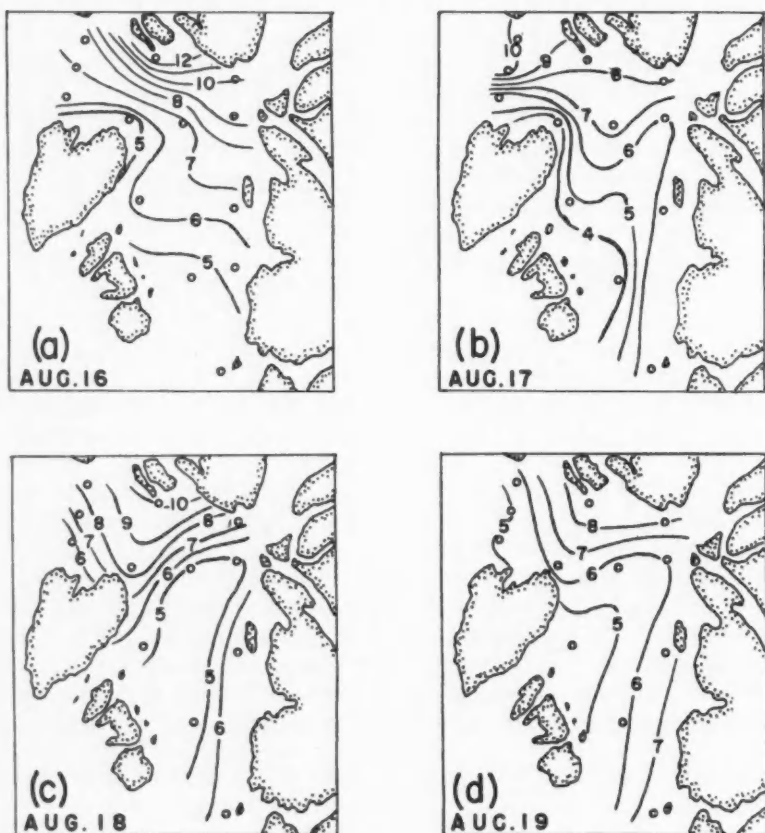


FIG. 13—Fresh water concentration (%), August 16-19, 1948.

and have not been illustrated. However, those in the northern half indicate relatively large variations from the average. These plots are shown in Fig. 13(a), (b), (c), and (d).

On August 16 *C* varied from 4.1% at station 26 to 12.7% at station 29. The interesting feature of this plot is the tongue of relatively high fresh water concentration extending westward towards Hudson Bay Passage, which suggests some movement in this direction.

The distribution of fresh water on August 17 has changed considerably from the previous day. The 6% *C* line best illustrates the observed change. It has now been displaced further northward in the sound to be replaced by more saline water. However there has been an increase in fresh water concentration along the Tsimpsean Peninsula. The maximum *C*, 10.5%, observed at station 36, in the middle of Dundas Passage, has decreased from the previous day.

The August 18 plot exhibits little change from that of the day before in the central part of the sound but the maximum was again observed at station 29. It seems most probable that this maximum represents a new cell of brackish water which has moved out of Portland Inlet and the water which had the highest concentration the previous day has moved out of the area.

On August 19 *C* varied from 4.3% at station 25 to 8.7% at station 29. This was the minimum variation observed in the sound during the 4-day survey.

These individual surveys then indicate a rather large variation from the average distribution and suggest clearly the tendency for some southwestward movement of fresh water. This is also indicated in the average distribution of fresh water (Fig. 3) as noted from the "shape" of the 5% *C* line.

It should be pointed out that during this period the Skeena River water contributed considerably to the distribution of fresh water in the central and northern part of the sound. Consequently, the patterns of fresh water concentration observed cannot be interpreted on the basis of Nass River discharge alone.

(9) SEPTEMBER 8-SEPTEMBER 10

This was the last survey made during the expedition and consisted of a fairly complete coverage of the sound. Surface samples were taken and bathythermograph casts usually made for three positions between stations, consequently a fairly detailed surface salinity pattern is available.

The average fresh water concentration is presented in Fig. 14(c). *C* varied from 0.0% in the south central part of the sound to 15.9% at station 29. The pattern was very similar to the average presented for August 10-19, but had a much higher fresh water concentration. The 10% isopleth approximately replaced the 7% one of August 10-19 and a similar displacement of the others was observed. There were indications also of some flow through Brown Passage.

The presence off Inverness Passage of water more saline than the mean may in part be due to the tide, because observations in the southern part of the sound were made at high water ± 3 hours, whereas those in the approximate latitude of Tugwell Island were made at low water ± 3 hours. This fact would explain the abnormal distribution of fresh water in this part of the sound. The

general higher fresh water concentration, however, is attributed to the increase in discharge of both the Nass and Skeena during the first 5 days of September.

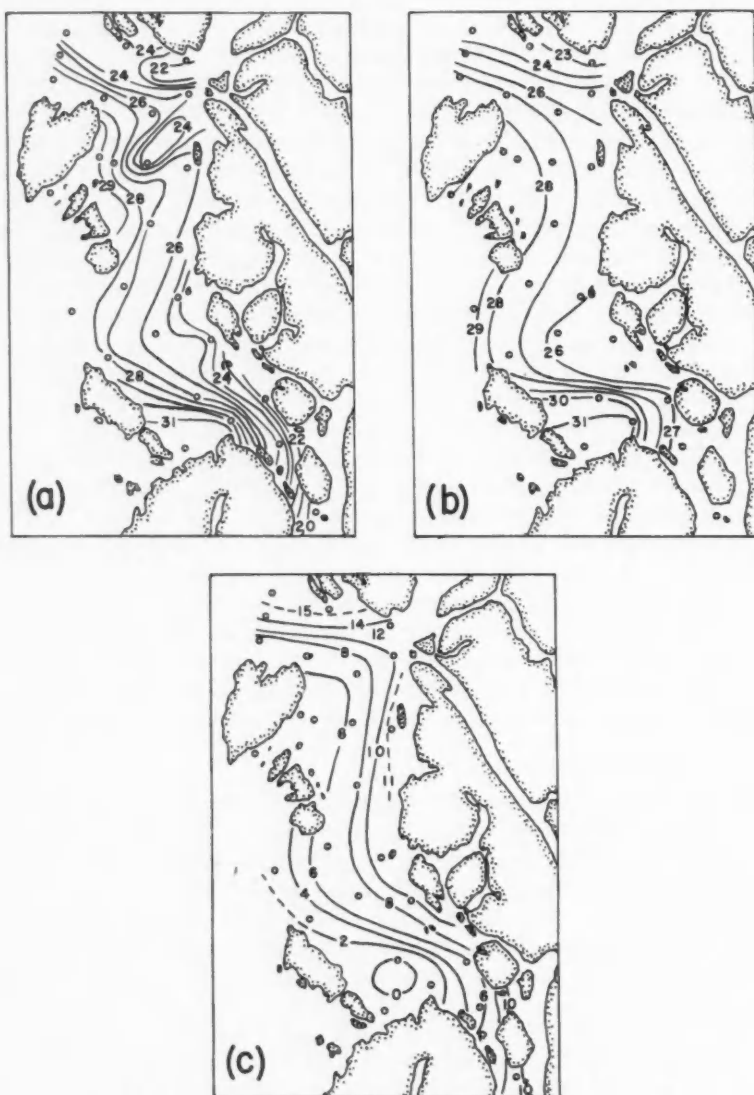


FIG. 14—Salinity and fresh water concentration, Sept. 8–10, 1948.

- (a) Surface salinity.
- (b) Salinity at 6 feet.
- (c) Fresh water concentration.

The surface salinity pattern is illustrated in Fig. 14(a). The salinity likewise was lower than the average for August 10-19, varying from 19‰ at the station just south of Kennedy Island to 31.9‰ at station 45 located just north of Edye Passage. The explanation for the distribution in the southern part is similar to that given for the distribution of fresh water. In the northern area a cell of low salinity water was present near station 52. A tongue of low salinity water also extended from Portland Inlet. The cell of brackish water appears to have moved into the area since the previous day, consequently the pattern illustrated is quite possibly not synoptic. It is more likely that this cell of low salinity water was, on the previous day, the tongue of water which is indicated to be moving out of Portland Inlet. The decrease in salinity was presumably due to the sudden increase in Nass River discharge during September 3 and 4.

In Fig. 14(b) the salinity pattern at 6 feet is shown. It is interesting to note that while the pattern is very similar to that of fresh water concentration (Fig. 14(c)), it shows a marked difference from the surface salinity pattern (Fig. 14(a)), especially in the northern part of the sound. The cell of low salinity water indicated in the surface pattern is entirely absent at 6 feet; this emphasizes the shallowness of the cell of brackish water.

The September 8-10 survey can be summarized as follows:

A. The average fresh water concentration in the sound was greater than that for average river discharge conditions. This correlates with the observed river discharges.

B. The observations cannot be considered as synoptic. The crowding of the isopleths in the southern area was accentuated due to differences in tidal phases. The shallow brackish layer in the northern area is associated with the increase in Nass River discharge. The cell observed on September 10 is associated with the tongue which extended from Portland Inlet on the previous day.

C. The fresh water concentration pattern is a fair approximation to the mean distribution during this period.

These observations on September 10 concluded the survey of Chatham Sound.

ANCHOR STATIONS

During the course of the survey, seven anchor stations were occupied. The locations of these are shown in Fig. 4.

Observations of temperature and salinity in the water column were made at intervals of 1 to 2 hours. From these observations the dominant factors determining the structure of the water and its variations should appear.

The salinity and temperature of the water in Chatham Sound at any particular place and time are determined largely by: (i) river discharge, (ii) tide, (iii) wind, (iv) internal waves.

ANCHOR STATION 80

Station 80, located just south of Digby Island, was the first to be occupied. Observations were commenced on July 2 and continued for approximately 25 hours, with observations being made at intervals of about 1½ hours. Figure 15

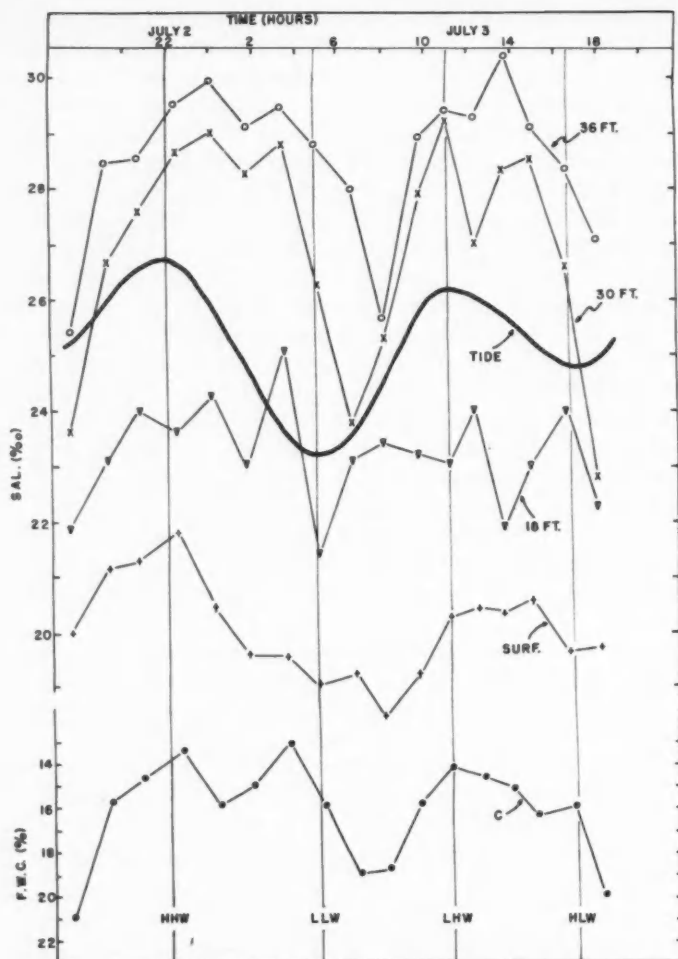


FIG. 15—Variation in salinity at surface, 18, 30, and 36 feet, and fresh water concentration at anchor station 80, July 2-3, 1948.

shows the variation of salinity with time at the surface, 18, 30, and 36 feet and in the same diagram the variation of fresh water concentration and the tidal height are shown.

The surface salinity curve follows that of the tide, illustrating that the tide is the predominant factor at this time in determining the fluctuations at the surface.

The salinity variation at 18 feet exhibits little or no correlation with tide.

The transition zone between the upper brackish layer and the deeper more saline water, which is indicated by the sharp vertical salinity gradient, is observed to be at this depth. Considerable mixing and transfer of water must have been occurring across the boundary between these layers and apparently masked any tidal effects. (Presumably most of the energy supplied for mixing is derived from tidal forces, but this secondary effect is not of necessity in phase with the tide.)

The variations in salinity at 30 and 36 feet, and in fresh water concentration in the upper 60 feet, all follow the tide curve closely. It is evident from these curves that a fair degree of correlation exists between the curves of salinity, fresh water concentration, and tide.

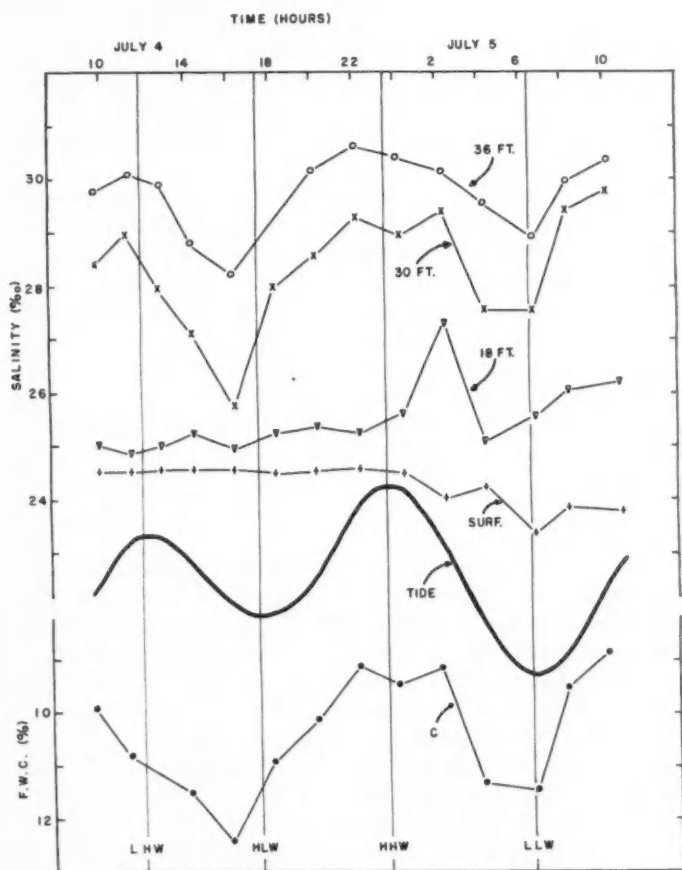


FIG. 16—Variation in salinity at surface, 18, 30, and 36 feet, and fresh water concentration at anchor station 81, July 4-5, 1948.

The relationships of the depth of the 27‰ isohaline and the 50°F. isotherm, versus time, were also drawn. These showed essentially the same fluctuations as have been illustrated for the variations at a particular depth.

While in each case the period of oscillation was about equal to that of the tide, the phase of the salinity, fresh water concentration, and temperature curves lagged behind that of the tide by about 90 degrees.

The curves then all exhibit the same general tendencies, making it evident that the tide was the principal factor in controlling these variations.

ANCHOR STATION 81

On July 4 and 5 station 81 was occupied over a period of 24 hours. Plots similar to those for station 80 were made and a few of these are illustrated in Fig. 16 from which the following items are noted:

- (a) Surface salinity variation is small, showing no tidal periodic tendencies.
- (b) Salinity at 18 feet does not show any tidal variations.
- (c) Salinity variations at 30 and 36 feet again correspond fairly closely with the tide curve.
- (d) Variation in fresh water concentration follows the tide curve closely.
- (e) In each case where correlations existed, the phase of the salinity, temperature, and fresh water concentration curves were advanced in phase relative to the tide curve by 60 to 90 degrees.

Plots of depth versus time for the 52°F. temperature and 26‰ salinity (not illustrated) also agreed closely with the tide curve.

The small variation in surface salinity with time as compared with that of station 80 is to be expected since station 81 was located further from a fresh water supply and consequently the horizontal gradient of salinity was smaller. It also suggests the possibility of a net flow over the tidal cycle.

ANCHOR STATION 82

On July 5, 6, and 7 station 82 was occupied for a period of 40 hours. The variation with time of the depth of the isohalines is illustrated in Fig. 17(a), and in Fig. 17(b) the variation of salinity with time at selected depths is shown. These plots do not show any correlation with tidal cycles. Figure 17(c) shows the variation in depth of the 29‰ salinity line, and the 49°F. isotherm together with the variation in fresh water concentration. The curves are observed to correlate very closely with one another, though not with tide. The complicated variations could be accounted for by internal waves alone but it is quite possible that the structure indicated was the result of a combination of several factors (e.g. tide, river discharge, wind, and internal waves).

On July 22 and 23 station 82 was again occupied for a period of 25 hours and, as during the previous occupation, no correlation with tide was evident. Surface salinity fluctuated more widely than on July 5, 6, and 7. No explanation for this difference appears.

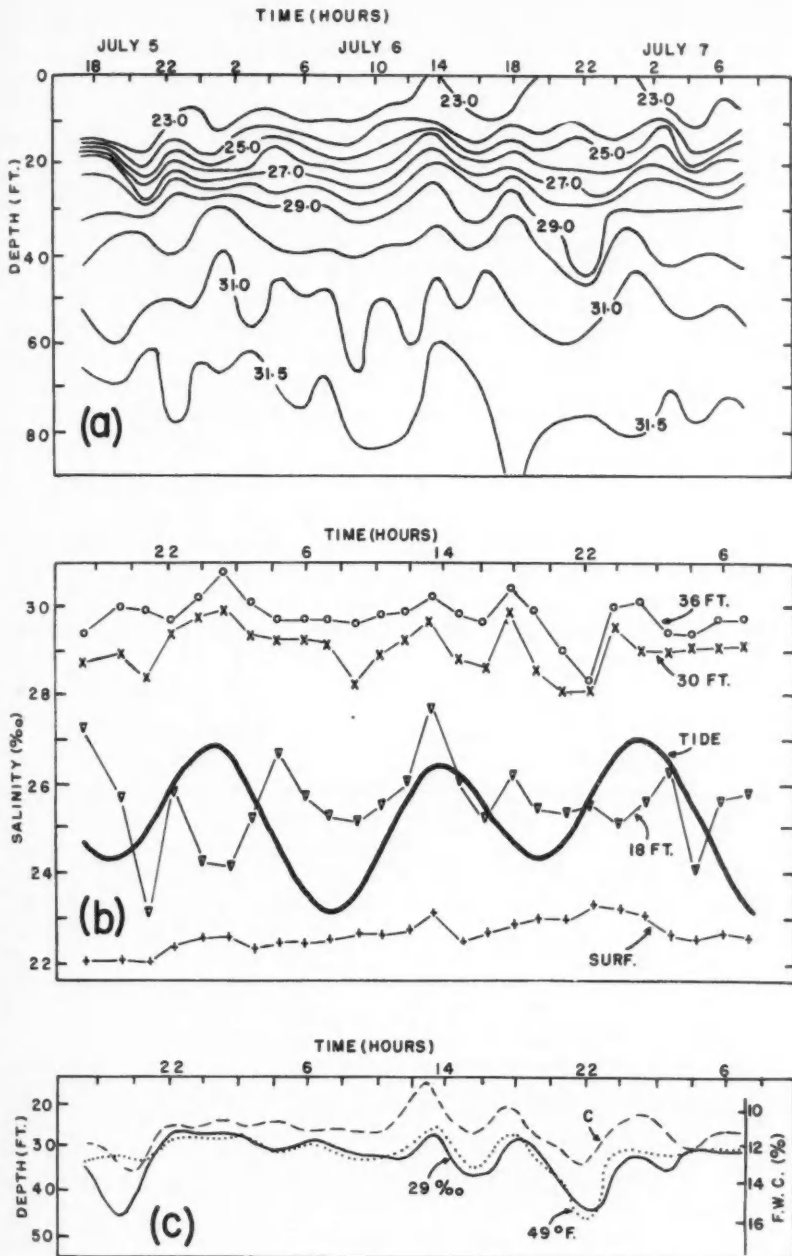


FIG. 17—Anchor station 82, July 5-7, 1948.

- (a) Salinity section.
- (b) Variation in salinity at surface, 18, 30, and 36 feet.
- (c) Variation in fresh water concentration, depth of 49°F. isotherm, and 29‰ salinity isopleth.

ANCHOR STATION 113

On August 7 and 8 the ship was anchored at station 113 for a period of 25 hours. This station is located very close to station 80 and therefore for comparison the two stations can be considered as identical.

Surface salinity variations, etc., are illustrated in Fig. 18(a). These curves are seen to have a variation with a period similar to that of the tide. However,

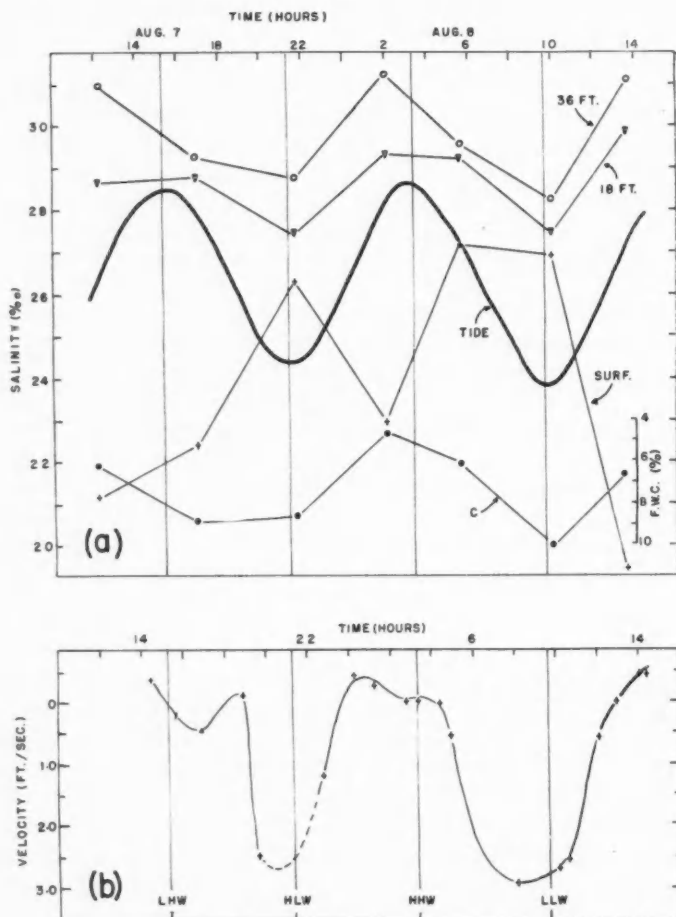


FIG. 18—Anchor station 113, August 7-8, 1948.

(a) Variation in salinity at surface, 18, and 36 feet, and in fresh water concentration.

(b) Surface velocity in direction 315° (true).

the surface salinity curve is approximately 180 degrees out of phase with those of tide and of salinity and temperature at 18 and 36 feet. Such a phase difference could be explained if the surface and deeper currents were in opposite directions. Surface salinity fluctuations from high to low water were much greater than during the July 2 and 3 occupation of station 80. The wider fluctuations are due possibly to the decrease in Skeena River discharge, which would result in greater surface salinity gradients in this region at this time than during higher river discharge levels.

While the variation in salinity, temperature, and fresh water concentration at station 82 exhibits no correlation with the tidal cycle, variations at all other stations do show an approximate correlation with that of the tide. These complicated fluctuations of salinity and temperature could have been due, in addition to tide, to any one or a combination of different factors such as wind, river discharge, and internal waves. Sufficient data of an intensive nature are not available to determine the relative importance of the various factors.

ANCHOR STATIONS 75 AND 76

On August 24 and August 31 stations 75 and 76 respectively were each occupied for a period of about 12 hours, primarily for current observations. Salinity and fresh water concentration variations are illustrated in Fig. 19(a) and 20(a). The variations agreed closely with the tidal phase; however, the brief periods of occupation prevent conclusive deductions from being drawn.

CURRENT OBSERVATIONS

Occasionally surface current observations were made at some of the hydrographic stations occupied during the surveys. More detailed direct observations were made at anchor stations 113, 75, and 76, occupied on August 7 and 8, 24, and 31 respectively. Measurements were made at the surface, 15, 30, and some at 60-foot depths, using free current drags.

Calculations of currents from temperature and salinity observations have also been made. The results of these calculations will be presented and discussed later.

STATION 113, AUGUST 7-8

Observations of velocity were made at the surface and at a depth of 30 feet. The predominant flow was observed to be in the direction 315° (true). Figure 18(b) illustrates the surface velocity along this line. The surface current varied from a value of -0.40 ft./sec. at 2 hours before LHW to a maximum of 2.9 ft./sec. about 2 hours before LLW. The mean velocity along this line during a 24-hour period was 1.0 ft./sec. Velocities at 30 feet were similar in phase to those at the surface, although the range was somewhat greater, varying from 0 to 4.0 ft./sec.

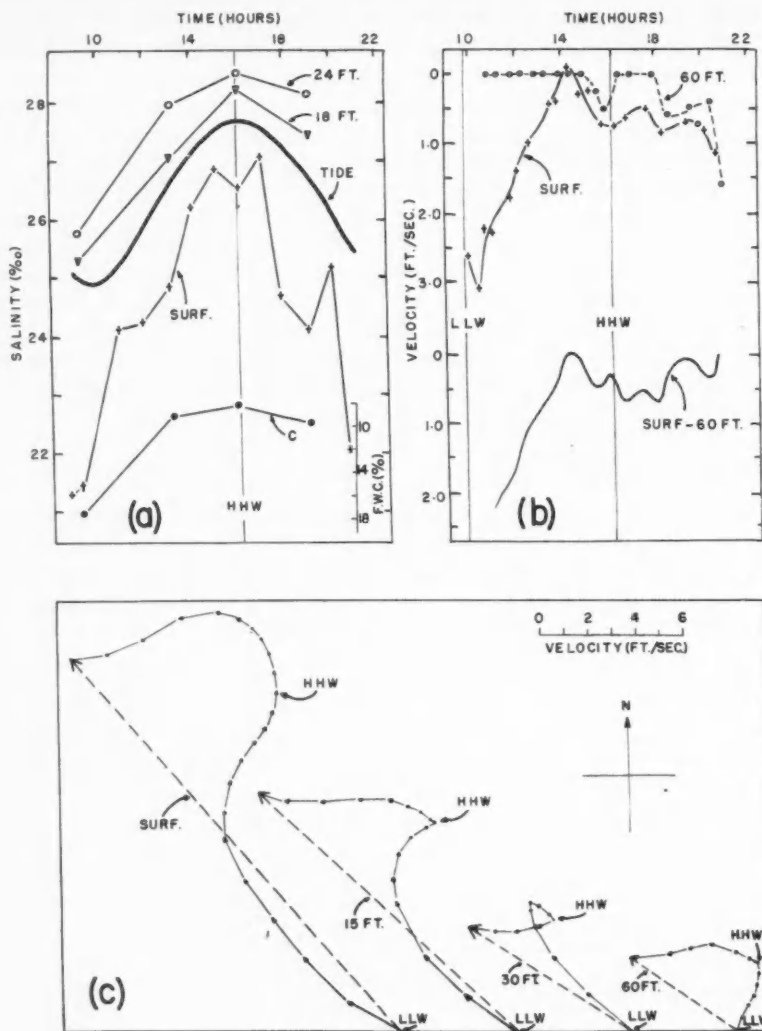


FIG. 19—Anchor station 75, August 24, 1948.

- (a) Variation in salinity at surface, 18, and 24 feet, and in fresh water concentration.
- (b) Velocities in direction 315° (true).
- (c) Hodographs of velocities at $\frac{1}{2}$ -hour intervals.

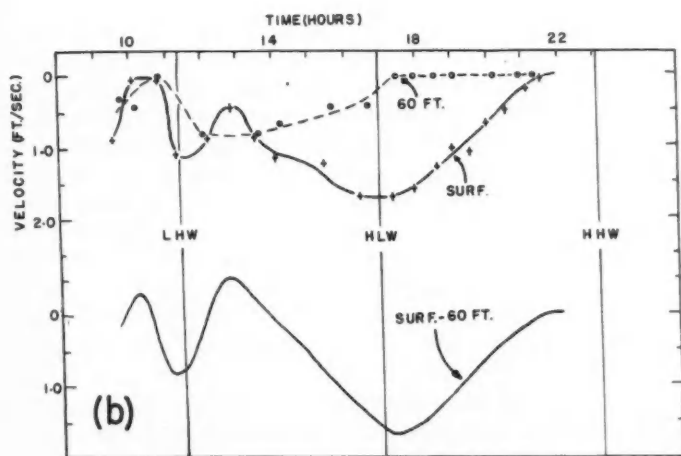
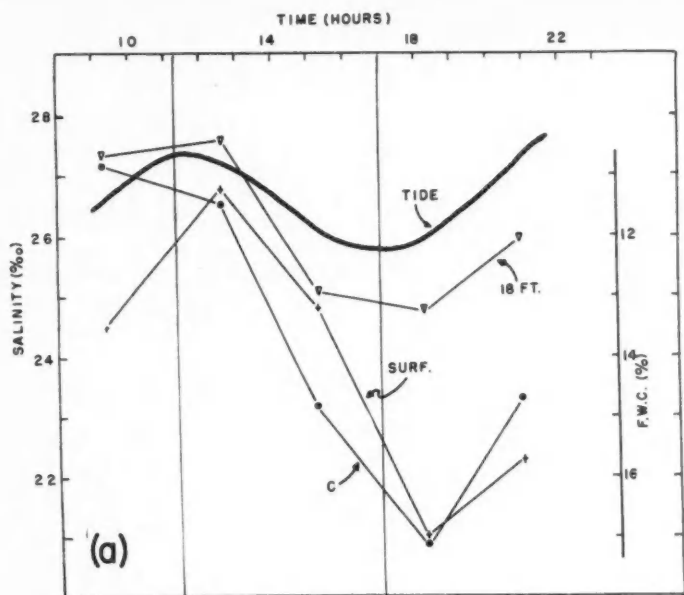


FIG. 20—Anchor station 76, August 31, 1948.

(a) Variation in salinity at surface and 18 feet, and in fresh water concentration, at anchor station 76.

(b) Seaward velocities (from Cameron, 1951).

STATION 75, AUGUST 24

On August 24 station 75 was occupied for a period of approximately 12 hours. Hodographs of the velocities at half-hour intervals for 0, 15, 30, and 60 feet are presented in Fig. 19(c). These indicate that the resultant flow at all depths down to 60 feet was approximately in the direction 315° (true). The mean current in the direction of resultant flow over approximately a 12-hour period (HLW to LLW) was 0.94 ft./sec. at the surface, 0.69 at 15 feet, 0.40 at 40 feet, and 0.17 at 60 feet.

In a narrow estuary in which lateral variations can be neglected, a flow of the deep, more saline water towards the head of the estuary is required in order to maintain the observed salinity structure in the upper layer. Tully, in his study of Alberni Inlet (1949a), observed that this up-inlet flow occurred well above 60 feet. It is possible that since this area of Chatham Sound cannot be considered in two dimensions, the necessary flow of the deep water is from the southeast, consequently resulting in a net flow in the same direction as that at the surface. Alternately, it is quite possible that a flow of water at depths greater than 60 feet was in the reverse direction to the surface current. Examination of the salinity profile indicates that there was still some dilution due to fresh water at 60 feet.

For comparison of this station with station 113 currents at the surface and 60 feet in the direction 315° (true) are presented in Fig. 19(b).

STATION 76, AUGUST 31

On August 31 the ship was anchored near Wales Island, off Portland Inlet. Cameron (1951) has reported on the results of these observations.

The seaward velocity at the surface and 60 feet is illustrated in Fig. 20(b). The surface current was seaward over the period of observation, fluctuating in speed near LHW, reaching a maximum at HLW, and decreasing to zero at HHW. The mean seaward surface velocity averaged over a period of 12 hours was 0.81 ft./sec. The current at 60 feet was less and different in phase. The average velocity was 0.25 ft./sec., making a mean difference in seaward velocity of 0.56 ft./sec. between the surface and 60 feet.

Further use of these current observations will be made later.

SALINITY STRUCTURE AND MIXING MECHANISM

If the vertical distribution of salinity at one position is examined it will be found that the water is arranged in a series of strata. The upper layer is the least saline, while at greater depths the water becomes more and more saline and in general undiluted sea water is found within 100 feet of the surface. Although, in each case, the total range in salinity from surface to bottom is usually of the same order of magnitude, the number of distinct layers observed will vary with position and time. While the two-layer system, having a transition region where the salinity gradient increases sharply from low salinity at the surface layer to higher salinity in the deeper water, is the most common, there may be as many as four or five distinct layers. In each case they are arranged in the order of increasing density with depth. This stratification occurs because, in large bodies

of water, sufficient energy to mix the waters completely is not available. Work has to be done against gravity to move the deep saline water up to the surface zone. A parcel of water then may retain its salinity for long periods of time unless sufficient energy is available to mix it with the surrounding water. Three factors, tide, river discharge, and wind are capable of supplying energy for mixing. Of these the tide is probably the most important factor.

Tully (1949a), in his study of Alberni Inlet, has observed some interesting relationships between the estuarine properties and both the tidal motions and river discharge. He has observed that a linear relationship exists between tidal velocities and the increase in sea water per unit volume of fresh water in the upper layer, and has deduced that the decreasing proportion of fresh water toward the mouth of the inlet is the result of the rate of mixing due to the tide alone.

Cameron (1948b) states: "From visual observation of the numerous eddies and rips that are present in the Skeena, near its mouth, one might conclude that in this locality at least, the water would be fairly uniform from top to bottom. But examination of the vertical distribution of salinity shows that this is not the case." In Fig. 21 the distribution of fresh water in a vertical section through the main channel of the Skeena River, from a position near the southern tip of Kennedy Island to a point just off the Ecstall River mouth, is presented. The section was made during a flooding tide on September 7, and illustrates conditions during the influx of sea water into the river.

The most outstanding feature of the section is the general inclination of the lines of constant fresh water concentration. For example the 50% C line intersects the bottom 4 miles upstream from its position at the surface. It is noted also that the isopleths are not equally spaced. The greatest change in horizontal concentration at the surface appears just seaward of Inverness Passage, between stations 1B and 97. Along the bottom the greatest horizontal gradient is near station 97. The regions where concentrations change rapidly with distance represent boundaries established by the movement of water through Inverness and Marcus Passages. As a result of these passages, there must be some flow across the main channel at all stages of the tide. When the tide is flooding, sea water enters the river through the three channels, moves in under the river water, lifting it to its high tide level and effectively damming up the river water. The influx of sea water increases mixing, but the cross-section presented indicates that it is far from complete.

At high tide, upstream from Inverness Passage, the surface water is nearly fresh, while the bottom waters are considerably more saline. During the ebb tide the whole water column from top to bottom is moving seaward. Inverness Passage being furthest upstream and somewhat shallower than the other passages, discharges into Chatham Sound water of relatively high fresh water concentration. Marcus Passage is further to seaward and therefore discharges more saline water than Inverness Passage. The most saline water of all discharges through the main channel. Thus the passages contain decreasing amounts of fresh water from north to south.

During the next flooding tide water in each passage is pushed upstream by the invading sea water, and the regions where these streams of different fresh

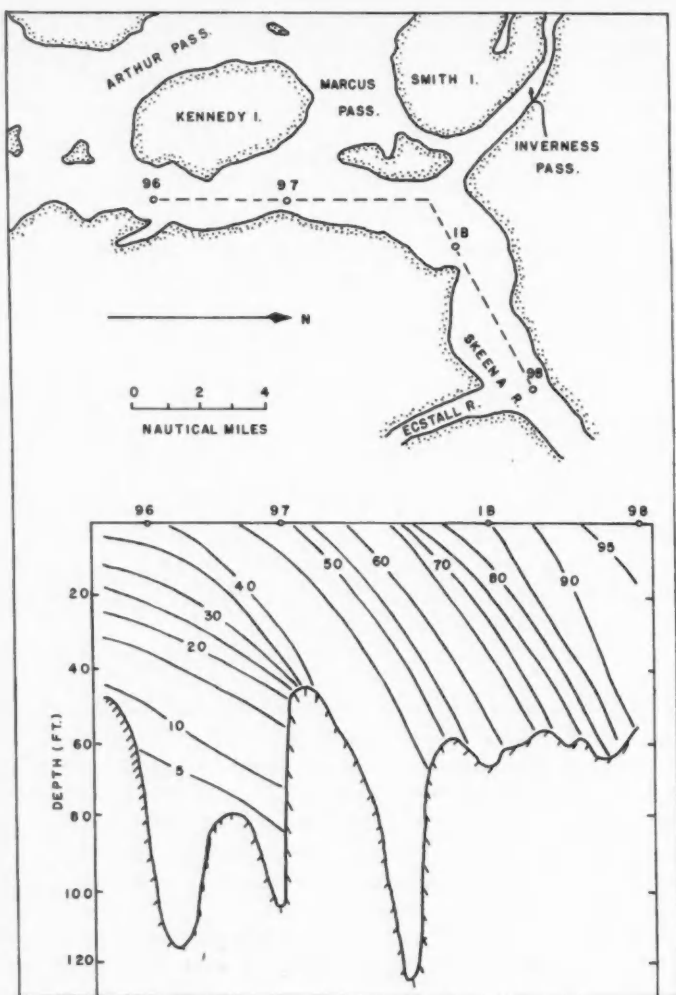


FIG. 21—Fresh water concentration (%) in section through main channel of Skeena River, September 7, 1948.

water concentration join are marked by diffuse boundaries in which the fresh water concentration changes rapidly with distance. Although extensive mixing of waters occurs across these boundaries, they are not completely obliterated, being continually re-formed by the effect of cross-channel flow in these regions.

Boundaries of this type are also found in the open stretches of the sound and frequently can be identified, not only by the determination of salinity, but

by an abrupt change in the colour of the water. The water discharged from the Nass and Skeena is brackish and muddy. Since it is less saline than the water of the sound, it remains at the surface and tends to move seaward because of the continuous contribution of fresh water from the rivers. Mixing with the underlying water proceeds slowly and the brackish water spreads out laterally as it enters the sound.

Tidal oscillations are superimposed on the mean seaward movements of fresh water. While the exact nature of the tidal movement is not known, some

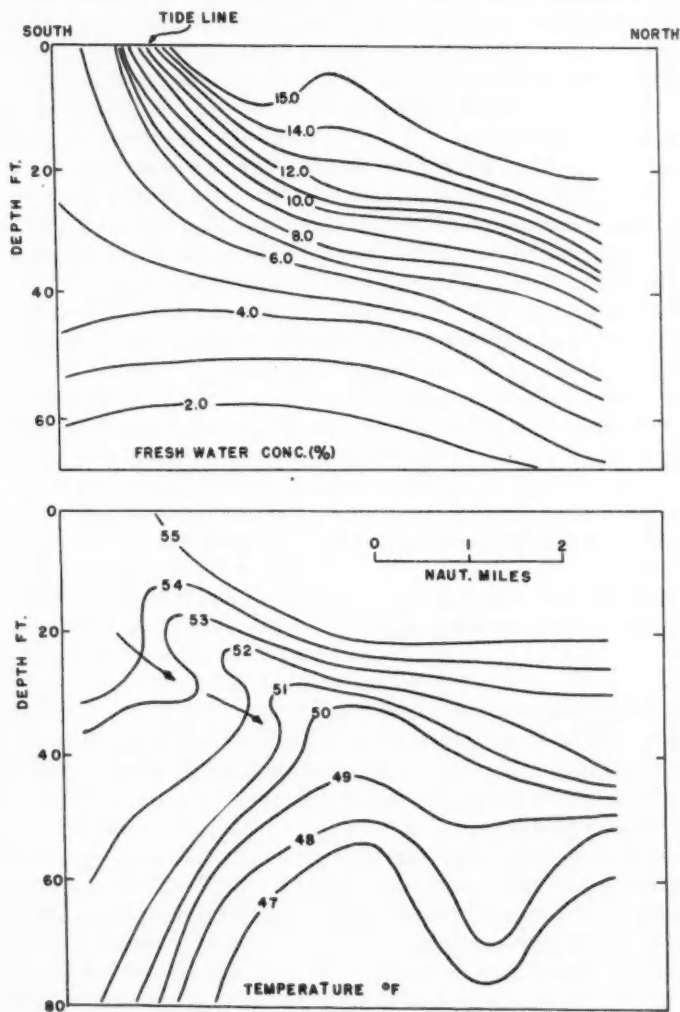


FIG. 22—Section from north to south across Dundas Passage, July 21, 1948.

resultant effects have actually been observed. Very often it has been noticed that at the boundary between the river water and sea water, floating debris such as seaweed, bark, and even logs, stretches for several miles. These narrow, clearly marked lines are known as "tide lines." The fact that the floating debris remains together indicates that there is a convergence of surface water from both sides, toward the lines. Consequently mixing and sinking must be occurring at the boundary.

The surface water is never completely bounded by a continuous line marking the boundary where sinking occurs. Tidal currents vary in direction and magnitude, and mixing of the more saline water with the brackish water proceeds irregularly and at widely separated localities. On this account, several tide lines may be present at various positions in Chatham Sound at the same time.

An example of the character of the water below the surface in the vicinity of a tide line is illustrated in Fig. 22. This line was observed on the surface during the survey of July 21 and extended from a point just northwest of Dundas Island northeastward toward Garnet Point. The section was made just before high water in a line from Cape Fox to the north end of Dundas Island (between stations 28 and 27). The figure illustrating the fresh water concentration shows that a relatively brackish ($>15\%$ fresh water) layer of water extended across the passage, decreasing gradually in depth toward the south. At the position of the tide line the surface salinity increased abruptly, the surface water having a fresh water concentration of approximately 6% to the south of the line.

Examination of the temperature section also reveals the sinking of water at the tide line. This temperature distribution shows that sinking in the direction of the tongue (arrows), and gradual mixing between the upper and lower layers of water, were occurring.

In the section made on the same line just after high water, this tongue of warm water had completely disappeared, apparently the result of extensive mixing.

The examples cited above hence represent the chief mechanism whereby the brackish and more saline waters are mixed.

DYNAMICS

A. INTRODUCTORY REMARKS

At the present time the dynamics of the circulation of the open ocean are better understood than those of inshore waters. In the deep ocean the circulation may be determined with some accuracy by the use of the geostrophic equation, indicating that the predominant forces are those due to the horizontal pressure gradient and the Coriolis force. This permits the calculation of currents from observation of temperature and salinity.

Estuaries, however, present a more complicated problem since the applicability of the simplifying assumptions, that may legitimately be made when treating the open ocean, is questionable. The net flow of fresh water seaward, and the observed increase in salinity of the upper layer in the seaward direction, indicate that large pressure gradients along the direction of mean flow exist.

The relative importance of inertial and frictional forces in balancing these pressure gradients is not known with any degree of certainty. In shallow estuaries the bottom may introduce an important frictional effect and greatly influence the rate and degree of turbulent mixing. The kinematic requirements placed on the flow by the complicated boundaries must also be met.

For the case of long, narrow estuaries which can be treated in two dimensions the seaward decrease in fresh water concentration in the upper layer requires a net upward transport of the deeper more saline water, which in turn requires a net horizontal flow of this water in the reverse direction to that of the upper layer. Therefore some depth of no net horizontal motion between the two layers must exist. However, Chatham Sound presents a more complicated problem; the irregular coastline, the wide variations in depth, and the introduction of fresh water from two separate sources require a three-dimensional treatment. While the same movement of deep water as in long narrow estuaries must be occurring, it is only in narrow restricted localities that the actual mean flow can be inferred without making observations in that part of the water column.

Superimposed on the mean motion in an estuary are the acceleration and pressure forces established by the tidal oscillations. While the resultant periodic changes in sea level due to tidal forces are well known, the detailed effects of the tide in estuarine waters are not clearly understood. The problem is further complicated by the occurrence of non-periodic variation in river discharge and wind.

It appears then, that in the immediate future at least, a formal solution to the equations of motion will not be forthcoming. Therefore, simplifying assumptions will have to be made in an attempt to get a partial solution to the problem, and perhaps indicate more clearly future methods of attack.

Recent investigations of Chesapeake Bay by Pritchard (1952) have indicated that certain assumptions regarding the flow in this estuary are justified. He has observed a characteristic lateral gradient in salinity (across the estuary) and a characteristic slope in the surface of no net motion. He suggests that this lateral salinity distribution, resulting in a mean lateral pressure gradient, is in the main balanced by the Coriolis force related to the mean longitudinal motion (seaward). Extensive observation at three cross-sections in the James River estuary have shown that more than 75% of the Coriolis force associated with the mean longitudinal motion is balanced by the lateral pressure gradient related to the lateral salinity gradient. This same tendency for the development of a lateral salinity gradient has been observed at stations 30 and 31, located at the mouth of Portland Inlet; Cameron (1951) has reported on these observations. On the assumptions of geostrophic flow and no motion at 90 feet, surface velocities, volume transports, and fresh water transports were calculated for twelve occupations of these stations. Surface velocities agreed in magnitude and direction with those measured at an anchor station nearby (station 76). Fresh water transports were also considered to be in reasonable agreement with Nass River discharges measured at Aiyansh. If it is assumed that the upward transfer of salt occurs by virtue of the fresh water discharged into Portland Inlet, then it would

be expected that a decrease would occur when fresh water transports decreased. On the contrary, the calculations indicated that although the fresh water transport decreased in proportion to river discharge, no change in volume transport occurred. If this is actually the case, then it means that there must be an increase in the volume of salt water transported upward equal to the decrease in fresh water transported. The reason for this apparent increase in the upward transfer of salt is not evident.

B. PRESENTATION AND DISCUSSION OF CALCULATIONS

The calculations of surface velocities, volume and fresh water transports were made by Cameron (1951) for the occupations of stations 30 and 31 only. These are presented in Table II. The average surface velocity calculated for the twelve occupations was 0.75 ft./sec. This is in good agreement with observations made at anchor station 76 on August 31, which indicated an average net seaward velocity over a 12-hour period of 0.81 ft./sec.

In the present study dynamic calculations have been extended over most of the sound. Similarly, surface velocities, volume and fresh water transports have been deduced. These calculations were made with the idea of getting quantitative values of fresh water transports from section to section, and hence possibly obtaining values for the quantity of fresh water from each river passing through a particular section.

TABLE II*.—Seaward surface velocities, volume and fresh water transports out of Portland Inlet (calculated from dynamic height data at stations 30 and 31, assuming no motion at 90 feet).

Date	Surface seaward velocity	Volume transport	Fresh water transport
1948	<i>Ft./sec.</i>	<i>Cu. ft./sec.</i>	<i>Cu. ft./sec.</i>
June 1	0.76	500,000	172,000
2	0.20	251,000	73,500
3	0.35	604,000	126,000
4	1.03	336,000	117,000
8	0.81	284,000	75,000
9	1.66	570,000	130,000
10	0.29	185,000	22,300
11	1.62	384,000	107,000
Aug. 16	0.29	366,000	35,200
17	0.68	450,000	40,500
18	0.57	207,000	22,000
19	0.74	647,000	48,500

*From Cameron (1951): Transverse Forces in a British Columbia Inlet.

June 1–June 4

Calculations for June 1 data indicate a seaward velocity between stations 30 and 31 at the mouth of Portland Inlet of 0.76 ft./sec. and a fresh water transport of 172,000 cu. ft./sec. Calculations between stations 24 and 25 across Main Passage give a northerly surface velocity of 0.86 ft./sec. and a fresh water transport of 137,000 cu. ft./sec. Between stations 26 and 29 across Dundas

Passage a westward surface velocity of 2.3 ft./sec. and a fresh water transport of 398,000 cu. ft./sec. were calculated. In view of the assumptions involved, these calculated values appear reasonably consistent.

For June 2 similar calculations were made. These gave a seaward velocity between stations 30 and 31 of 0.20 ft./sec. and a fresh water transport of 73,500 cu. ft./sec., and between stations 24 and 25 a northward surface velocity and fresh water transport of 0.44 ft./sec. and 154,000 cu. ft./sec., respectively. Between stations 26 and 29 a westward surface velocity of 0.31 ft./sec. and a transport of approximately 400,000 cu. ft./sec. were calculated. These transports, especially between stations 26-29 and 24-25 have larger values than would be expected for the mean. However, it is quite possible that these values are real since the tide was ebbing when stations 25, 26, and 29 were occupied.

Calculations of velocity and transports for June 3 and 4 were also made, but only those for stations 30 and 31 are illustrated (Table II). The irregular values calculated for the other sections demonstrated that during such large and unsteady discharges of fresh water the assumption of the steady state is not justified.

June 8-June 11

Average dynamic height anomalies during this period in the upper 90 feet were calculated from temperature and salinity observations averaged for the four occupations of each station. These are presented in Fig. 23(a). The highest anomaly of 1.85 dynamic feet is at station 26 located near the northeast corner of Dundas Island while the lowest is 1.44 at station 27 located near the northwest corner of Dundas Island. Comparison of this plot with that of the average fresh water concentrations during the same period (Fig. 9) reveals a close similarity in pattern.

If it were assumed that flow was entirely along the lines of constant anomaly then a very strong transverse flow would be indicated. It seems more reasonable to conclude that a large component of flow took place across the lines of constant anomaly. The highest mean maximum located at station 26 is associated with the peak discharge of the Nass which was recorded at Aiyansh some 8 to 10 days earlier. This dynamic topography obviously does not represent a steady state, since from the pattern illustrated there is no way to maintain the high dynamic height observed at station 26. This "high" would be tending to reduce itself to the potential of the surrounding water by radial outflow and by mixing with more saline water.

The flow out of Portland Inlet during this period was unidirectional with a mean surface velocity of 0.84 ft./sec. and a mean fresh water transport of 99,000 cu. ft./sec. Assuming a 3-day lag for the passage of fresh water from Aiyansh to the mouth of Portland Inlet gives an average discharge of 91,000 cu. ft./sec. for the Nass River during this period.

While many of the transports calculated between various pairs of stations during this period were unreliable, it is of interest to note some of these calculations. Between stations 21 and 22 calculations showed a surface velocity of

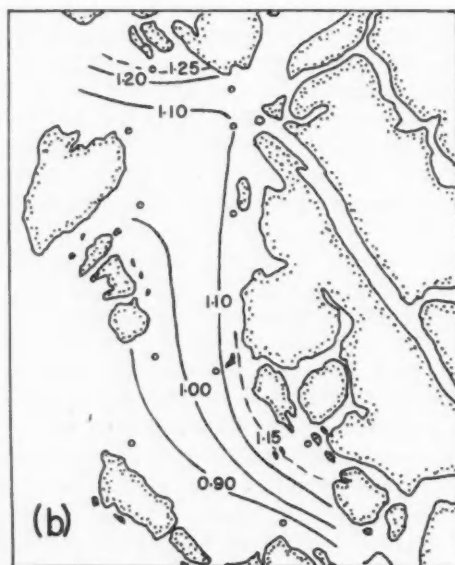
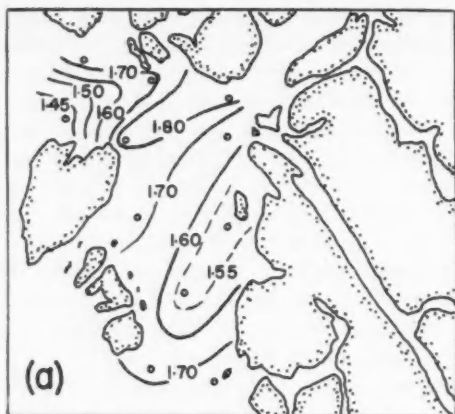


FIG. 23—Geopotential topographies of sea surface

(a) Average dynamic height anomaly (feet) relative to 90-foot level, June 8-11, 1948.

(b) Average dynamic height anomaly (feet) relative to 60-foot level, August 10-19, 1948.

less than 0.1 ft./sec., a net volume transport of less than 1,000 cu. ft./sec., and a fresh water transport of 8,000 cu. ft./sec. to the south. (A reversal in the direction of flow above 24 feet, relative to 90 feet, accounts for the net volume transport being less than the fresh water transport.) The small transport of fresh water compared with those calculated for the northern end of Chatham Sound appears significant and suggests that there is little or no Skeena River water moving northward along the Tsimpsean Peninsula. It is quite possible that this is the case during the freshet period when the Nass River water may effectively act as barrier to Skeena River water thus forcing it to move seaward through Brown and Bell Passages and the other southern passages.

August 10–August 19

The average dynamic height anomalies relative to the 60-foot level were calculated in the same manner as for June 8–11. These are plotted in Fig. 23(b). Anomalies varied from less than 0.86 dynamic feet at station 47 located near Triple Island, to greater than 1.25 at station 29 located just south of Garnet Point. The pattern is very similar to that shown for fresh water concentration during the same period (Fig. 3).

Table III shows the average surface velocities, volume and fresh water transports between various stations in the sound. The maximum average surface velocity was calculated to be 0.73 ft./sec. westward between stations 41 and 44. The surface current measured directly at stations 113 and 75 (located near station 41) was found to have a mean value over a tidal cycle of 1.0 ft./sec. Bearing in mind that 0.73 ft./sec. represents an average across the entire section and that the velocities near station 41 are probably higher than at station 44, the agreement appears satisfactory.

The average fresh water transport between stations 30 and 31 was found to be 31,000 cu. ft./sec. compared with the corresponding discharge at Aiyansh of 40,000 cu. ft./sec.

In most cases the calculated fresh water transports seem reasonable. One exception was between stations 41 and 44 where a value of 58,000 cu. ft./sec. was calculated. This appears to be too large in view of the fact that the mean Skeena discharge at Usk from August 6 to 9 inclusively was 33,000 cu. ft./sec. Possibly this large value was due to the assumption of a linear gradient of fresh

TABLE III.—Average surface velocities, volume transports, and fresh water transports (assuming no motion at 60 feet) between pairs of stations in Chatham Sound, August 10–19, 1948.

Stations	Surface velocity	Direction	Volume transports	Fresh water transports
	<i>Ft./sec.</i>		<i>Cu. ft./sec.</i>	<i>Cu. ft./sec.</i>
30–31	0.42	West	296,000	31,000
26–29	0.63	West	423,000	51,000
24–25	0.19	North	229,000	23,000
48–49	0.34	North	249,000	17,000
41–44	0.73	West	700,000	58,000
46–48	0.14	West	205,000	5,000

water between the two stations, whereas it is possible that the fresh water tended to be concentrated near station 41.

The fresh water transport between stations 24 and 25 was calculated to be 23,000 cu. ft./sec. Between stations 21 and 22 a flow of fresh water of only 17,000 cu. ft./sec. was indicated. It is quite probable that this difference may be accounted for by a considerable flow of fresh water between station 21 and the mainland. On the basis of these calculations and the previous discussion of fresh water distribution it is evident that about 70% of the Skeena River discharge was moving northward in Chatham Sound along the Tsimpsean Peninsula and out through Dundas and Hudson Bay Passages, 15% was leaving the sound through Brown and Bell Passages, and the remaining 15% was escaping through Edye Passage, Ogden and Grenville Channels.

September 9–September 10

On September 9 and 10 stations 24, 25, 26, 29, 30, and 31 were occupied. Calculation of surface velocities and fresh water transports, assuming no motion at 90 feet, are summarized in Table IV.

These calculations appear to be in reasonable agreement with river discharges and surface velocity measurements.

TABLE IV.—Surface velocities and fresh water transports (assuming no motion at 90 feet) between pairs of stations in Chatham Sound, September 9–10, 1948.

Stations	Surface velocity	Direction	Fresh water transports
	<i>Ft./sec.</i>		<i>Cu. ft./sec.</i>
30-31	0.59	West	29,000
26-29	1.0	West	182,000
24-25	0.39	North	68,000

C. VARIATION IN GEOPOTENTIAL SLOPE AT THE MOUTH OF PORTLAND INLET

Superimposed on the mean flow seaward of the surface layer are tidal movements. If the Coriolis force associated with the longitudinal motion is, in the main, balanced by lateral pressure gradients, then a periodicity in the geopotential slope equal to the tidal period should occur. On the basis of the calculations made for stations 30 and 31 (Table II) Cameron (1951) points out that a periodicity equal to the tide is not evident. However, since the differences in dynamic heights are determined by 2- to 4-foot differences in the level of the isohaline surfaces, then internal waves of comparable magnitude could mask any periodicity resulting from tides. Although these calculations indicate an unidirectional flow out of the inlet for the twelve occupations, two abnormally low values occur in the surface velocities and transports, notably on June 2 and June 10. Both of these sections were made on the flood tide a few hours prior to high water. It is suggested that these low values may represent instances in which the effect of the tide is noticeable.

On August 4 stations 30, 34, and 31 were each occupied twice. The first section was made during the first hour of the flood tide, while the second section

was made from 1 to 2 hours before low water. The directions and velocities of the current at the surface, assuming no motion at 60 feet, are presented in Table V. Station 34 is located approximately midway between stations 30 and 31. During the time the first section was made, surface velocities were directed up the inlet with an average value between stations 31 and 34 of 0.83 ft./sec. and between stations 34 and 30 of 0.13 ft./sec. The analysis demonstrated that during the time the second section was made the direction of flow had reversed and the greatest flow seaward was between stations 30 and 34 where an average value of 0.49 ft./sec. occurred. The velocity between stations 34 and 31 was 0.08 ft./sec. While this change in geopotential slope might have been due to tides, other factors, especially wind, could have caused this shift in the distribution of mass and consequently given a calculated up-inlet flow of surface water.

If a tidal periodicity in the dynamic heights does actually occur, then cross-inlet inertial and frictional forces must exist. However the data for the majority of the occupations implies that the Coriolis force and the transverse pressure gradient approximately balance each other. The relatively narrow, constant width of Portland Inlet would only require small accelerations and velocities to effect this transverse movement. The relatively low velocities required would keep the transverse shear small.

Insufficient data are available to determine the effect of the tide on the distribution of mass in Chatham Sound.

TABLE V.—Direction and magnitude of surface current (assuming no motion at 60 feet) at the mouth of Portland Inlet, August 4, 1948.

Stations	Pacific standard time	Velocity	Direction
	<i>Hour</i>	<i>Ft./sec.</i>	
31-34	0710	0.83	Up-inlet
34-30	0735	0.13	Up-inlet
30-34	1725	0.49	Down-inlet
34-31	1745	0.08	Down-inlet

SUMMARY AND CONCLUSIONS

Data have been presented to show the distribution of fresh water and surface salinity in Chatham Sound during the period from May to September, 1948. The results of salinity, temperature, and current observation at anchor stations, as well as dynamic calculation, have also been described.

From the study of these surveys the following conclusions have been drawn:

(1) During normal river discharge conditions, only a small proportion (less than 30%) of Skeena River water reaches Dixon Entrance and Hecate Strait through the central and southern passages. Approximately one-half of this appears to be escaping through Brown and Bell Passages and the remainder through Edye Passage, and Ogden and Grenville Channels. The bulk (more than 70%) of Skeena River water moves northward past Tugwell Island, along the Tsimpsean Peninsula, merges with the Nass River discharge, and finally leaves

Chatham Sound through Dundas Passage and to a lesser extent through Hudson Bay Passage.

(2) The peak discharge of both rivers is reached in late May or early June and during this time the concentration of fresh water in the sound is three to four times the average. Fresh water leaves the sound through all the passages and channels, although Dundas Passage transports the largest amount of any single passage. During this period, Nass River water extends as far south as Melville Island.

(3) It seems quite probable that during freshet conditions, the presence of increased amounts of Nass River water in the northern part of the sound acts as a barrier which prevents any extensive movement of Skeena water northward past Tugwell Island. The fact that there is evidence of a fairly effective barrier during this particular year (1948) when the peak discharge of the Skeena was much greater than the normal peak, while the Nass did not reach the same relative abnormal height, suggests that during the average freshet conditions the Nass may act as an even more effective barrier to Skeena River water than has been indicated in the 1948 survey.

(4) Observations extending over a period of several days cannot be considered as synoptic when the rivers fluctuate; hence diagrams showing the distribution of fresh water or salinity in the entire sound, for which data gathered several days apart have been used, cannot as a rule be considered properly synoptic.

(5) Anchor stations reveal that in most cases variations in salinity, temperature, and fresh water concentration correlate with tidal variations.

(6) Dynamic height anomaly plots give essentially the same pattern as fresh water concentration. An apparent balance exists between Coriolis force and transverse pressure gradients at the mouth of Portland Inlet. There also is an apparent balance in the sound during normal discharge conditions. However, during freshet conditions cross-isobaric flow is probably dominant. Calculations of transports, assuming a steady state, led to anomalous values which appeared obviously erroneous.

(7) From the various surveys there appears to be an average time lag of from 2 to 5 days from the time a parcel of water was at Aiyansh until it reached station 30 at the mouth of Portland Inlet, the time required being a minimum during maximum fresh water discharges.

The average time lag between Usk and station 41, located south of Digby Island, appears to be of the order of 3 to 6 days, varying with the discharge.

Naturally, factors such as variation in wind and tide would decrease or increase these times as the case may be.

(8) During periods of unsteady river discharges large cells of relatively fresh water are discharged into the sound. These are gradually dispersed as they move seaward by spreading out laterally and mixing with more saline water. Energy to do this is supplied by the tides, winds, and the potential and kinetic energy of the fresh water itself.

(9) Direction, strength, and duration of the wind are probably of considerable importance in causing wide variations from the average.

(10) The discussion of the data has indicated clearly the difficulties involved in obtaining a reliable synoptic picture of an estuary of this size and type. Since usually only one ship is available to carry out a survey, the area which can be covered in a short period of time is limited. While a general survey of the entire area is required in order to determine the gross features of the distribution of properties and of the circulation, surveys covering a smaller area but of a more intensive nature are required if a clearer understanding of the relative importance of the several factors influencing the circulation is to be obtained. The observations at the anchor stations in the survey illustrate the important role which the tides play in determining the distribution of salinity and temperature at any particular time. A more accurate evaluation of the part played by the tidal currents in transport of fresh water could be obtained if observations (salinity, temperature, currents) across selected sections were taken over a period of several tidal cycles.

In the 1948 survey the observations were made down to depths of 90 or 150 feet at most. A better understanding of the dynamics of the circulation would result if observations were extended, where possible, to deeper levels. From these a knowledge of the depth of no net motion, and the movement and relative magnitudes of the net inward transport of the deeper water in the various passages, could be gained. The direct observation of currents would serve, apart from its primary value of indicating the circulation, as a check on dynamic calculations and would ascertain with clarity the degree to which geostrophic flow exists in coastal waters of this type.

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Currents and Transport in Cabot Strait¹

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ABSTRACT

Currents and transport of volume and salt have been calculated by dynamical methods for Cabot Strait in the section extending from Cape North (Lat. $47^{\circ}02'N.$, Long. $60^{\circ}23'W.$), Cape Breton Island, to Cape Ray (Lat. $47^{\circ}37'N.$, Long. $59^{\circ}18'W.$), Newfoundland. A depth of 400 m. was assumed to be a level of horizontal isobars and zero motion. Five hydrographic stations were occupied in the section, providing data for current and transport calculations for four divisions of the section. Eight crossings of the section were made, observing spring, summer and autumn conditions through the years 1950-54. Features of the current distribution noted are: much variation from cruise to cruise, strongest currents in August and least in April and May, currents outward on the Cape Breton side, and most often inward on the Newfoundland side, and reversals with depth with no fixed pattern.

Inward and outward transports through the section were found to be of the order of 10^6 cu. m. per second and to vary considerably. Zero net transport was found in each instance to be attained by a small velocity adjustment comparable with errors inherent in the method of calculation. Salt balance calculations confirm these velocity adjustments.

INTRODUCTION

THE principal entrance to the Gulf of St. Lawrence from the Atlantic is Cabot Strait, extending from Cape North (Lat. $47^{\circ}02'N.$, Long. $60^{\circ}23'W.$) at the northernmost point of Cape Breton Island to Cape Ray (Lat. $47^{\circ}37'N.$, Long. $59^{\circ}18'W.$) at the southwest corner of Newfoundland. This distance is 56 nautical miles (104 km.). The section has a maximum depth of 480 m. while three-quarters of it is deeper than 300 m. Its cross sectional area is 35×10^6 sq. m. The Strait of Canso and the Strait of Belle Isle also give access to the gulf from the Atlantic. The former is very narrow and since 1954 has been closed by a causeway. The latter, with a minimum section 10 nautical miles (18 km.) wide and cross sectional area 10^6 sq. m., undoubtedly makes some contribution in the exchange of gulf and Atlantic waters and is deserving of further intensive study.

The currents in Cabot Strait have been investigated by the Canadian Hydrographic Service under the direction of the Superintendent of the Survey of Tides and Currents, an account being contained in the Reports of Progress of the Survey of Tides and Currents, 1895, 1896 and also in a report by Dawson (1913). These observations were made from an anchored vessel with an electrically registering current meter at a standard depth of 5.5 m. On the Cape Breton side a current to the southeast was found which, at Cape North, may be as great as 2 knots (1 m./sec.). At times this current extended 22 km. or more to the east of St. Paul's Island. On the Newfoundland side of the strait a movement of

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water into the gulf was observed, ranging in August from 0.25 m./sec. to 0.75 m./sec. at an anchorage 22 km. from Cape Ray.

Sandstrom (1919) carried out extensive studies of the hydrodynamics of Canadian waters as part of the Canadian Fisheries Expedition 1914-15 under the direction of Johan Hjort. His report included dynamical calculations of currents in the several sections of Cabot Strait. He recognized a general pattern of flow involving an outward Cape Breton Current and a compensating inward flow on the Newfoundland side. He found, however, a considerable diversity in the sections.

The Gulf of St. Lawrence Pilot (1946) reported an inward flow at the surface on the northeast side of Cabot Strait extending some 18 to 35 km. or even further from Cape Ray. The Pilot further stated "This current is by no means constant but it appears to have no relation to the rise and fall of the tide." On the southwest side of the strait a relatively constant outward current is reported with a velocity as great as 1 m./sec. at the surface. A similar description of currents in Cabot Strait is found in the Atlantic Coast Tide and Current Tables (1955).

The currents in the Strait of Belle Isle were investigated by Dawson (1907) from an anchored vessel using an electrically registering current meter at 5.5 m. depth, and a current drag at 46 m. The currents observed were described as primarily tidal in character and extending in strength well to the bottom. A phenomenon referred to as "dominant flow" was also observed, where, for several days at a time, a current of the order of one knot (0.5 m./sec.) persisted in either direction. It was assumed that this dominant flow was due to meteorological factors.

Huntsman, Bailey and Hachey (1954) drew attention to an additional feature of the currents in the Strait of Belle Isle—a progressive inward movement of water on the north side, together with an outward movement on the south side of the strait. A dominant outward flow of gulf water was also observed while an inward flow was inferred to have existed previous to the period of observation.

The currents in the Strait of Belle Isle are described in the Newfoundland Pilot (1952) as follows:

"The movement of the water in the Strait of Belle Isle is predominantly tidal in character. While under the control of the tide alone, it will turn regularly and will run with equal strength in each direction, the flood setting westward and the ebb eastward, but it is also complicated by a frequent tendency to a greater flow in one direction than the other. This complication called 'dominant flow' may be in either direction for several days in succession, or possibly a week or more, and at times, when the tidal stream is weak, it may be sufficiently strong to prevent the tidal stream from turning at all. The greatest rate of dominant flow, considered separately, observed in the course of one day in a westward direction averaged 1.75 knots and in an eastward direction 1.25 knots. No period of an astronomical character can be assigned to the dominant flow nor can it be explained as a wind drift, since the wind is frequently against it."

It is expected that the flow through Cabot Strait will be influenced by existing conditions in the Strait of Belle Isle. Variation in meteorological conditions

over the gulf will also influence this flow. Sea level changes of the order of 0.3 m. in a day are not unusual along the east coast of America (Marmer, 1930). Such a change over the gulf area of 2.1×10^6 sq. m. would involve a transport of 1.5×10^6 cu. m./sec.

OBSERVATIONS

A series of eight crossings of Cabot Strait made in the seasons 1950-54 by survey vessels of the Atlantic Oceanographic Group, the C.N.A.V. *Whitethroat*

TABLE I.—Location of hydrographic stations.

Station No.	Lat. N.	Long. W.	Depth	Interval
			m.	km.
34	46° 57.5'	60° 13'	65	23.4
35	47° 06'	59° 59.5'	325	24.8
36	47° 16.3'	59° 47'	465	23.4
37	47° 26'	59° 33.5'	475	25.0
38	47° 35'	59° 20.5'	275	

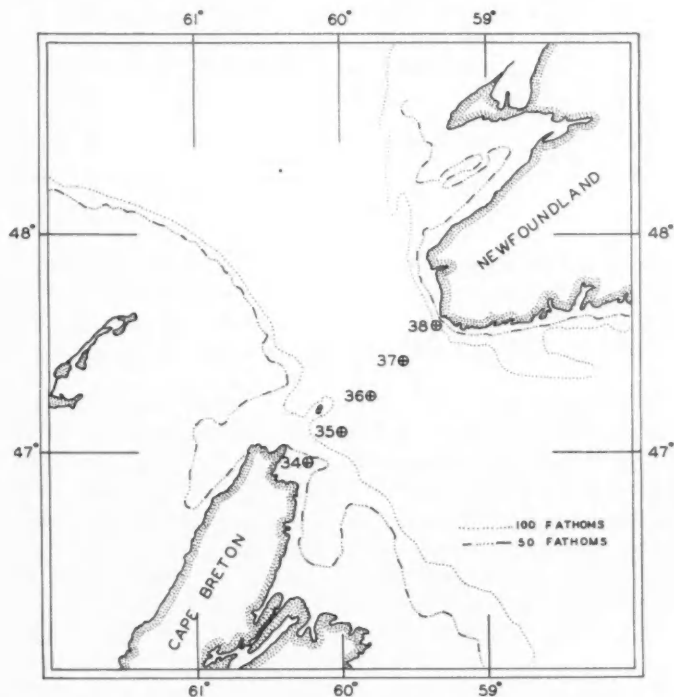


FIG. 1.—Cabot Strait showing location of hydrographic stations 34 to 38.

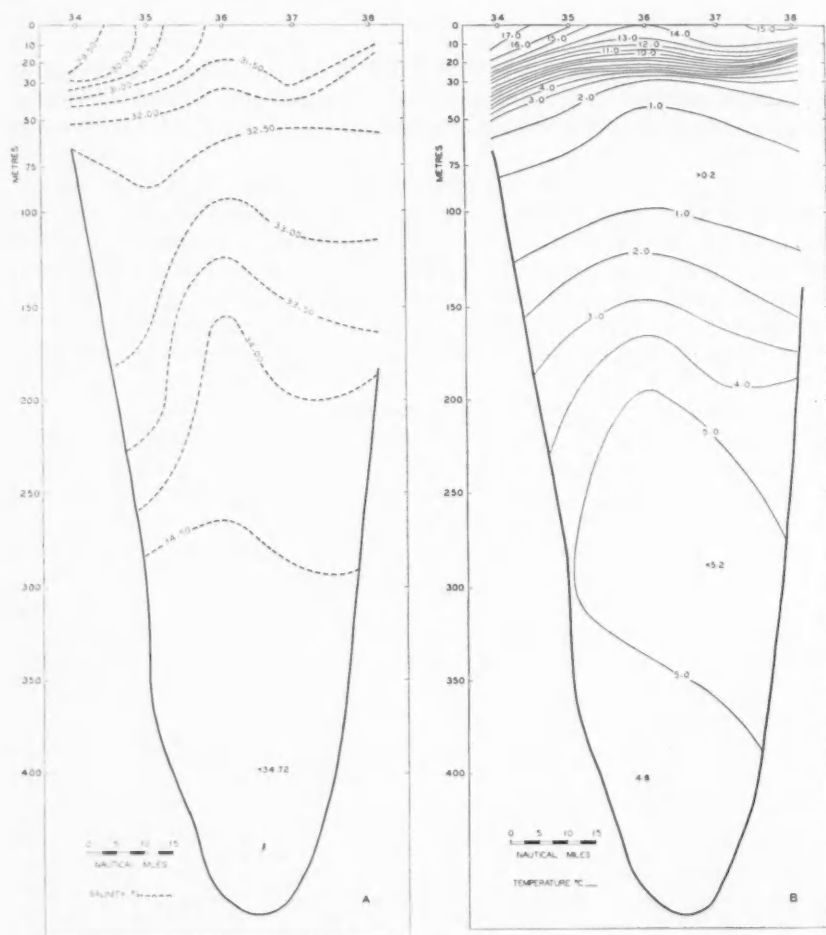


FIG. 2.—Distribution of salinity (A) and temperature (B) between stations 34 and 38 on 29 August 1950.

and C.N.A.V. *Sackville*, furnished data for the calculations of currents and transports by dynamical methods.

Five hydrographic stations, listed with locations, depths and intervals in Table I and shown on the chart (Fig. 1), were occupied in each crossing.

The eight crossings of the strait are listed in Table II by cruise number, ship and date, in order of seasons. The hours for stations 34 and 38 are given in the last two columns.

These data permitted current calculations at the standard depths of 0, 10, 20, 30, 50, 75, 100, 200, 300 and 400 m. for four intervals across the section.

Diagrams showing the temperature and salinity distributions for this section of Cabot Strait are presented in a manuscript report of the Atlantic Oceanographic Group (1954) for all the cruises listed in Table II, except for cruises S-16 of October 1953 and S-19 of April 1954. Figure 2 shows the typical configuration of temperature and salinity distributions in summer as represented by the results for cruise WT-2 on 29 August 1950.

TABLE II.—Cruise list with time of occupying the Cabot Strait section.

Cruise No.	Ship	Date	Hour (G.M.T.)	
			Sta. 34	Sta. 38
S-19	C.N.A.V. <i>Sackville</i>	25 Apr. 1954	10.09	18.42
S-7	"	15-16 May, 1952	05.38	21.45
WT-2	C.N.A.V. <i>Whitethroat</i>	29 Aug. 1950	07.50	17.14
S-10	C.N.A.V. <i>Sackville</i>	28-29 Aug. 1952	17.35	02.20
S-16	"	29-30 Oct. 1953	18.44	02.15
S-12	"	2 Nov. 1952	21.05	12.35
WT-5	C.N.A.V. <i>Whitethroat</i>	8-9 Nov. 1950	18.00	01.48
S-3	C.N.A.V. <i>Sackville</i>	11-12 Nov. 1951	23.40	08.33

METHOD

It has long been recognized that ocean currents might be calculated from the fundamental laws of dynamics. The distribution of density within the water masses, together with the effect of the earth's rotation, are the principal factors involved, assuming that frictional influences are negligible and that a steady state exists.

Peslin (1872) and Mohn (1887) made early attempts to calculate ocean currents from the slopes of the isobaric surfaces. Sandström and Helland-Hansen (1905) developed the dynamic theory of currents in a more satisfactory way, based on V. Bjerknes' (1898) extension of Lord Kelvin's (1869) circulation theorem. They devised a convenient technique for analysing the data. This theory is developed in various standard references: Sverdrup, Johnson and Fleming (1942), Hachey (1934), Sandström and Helland-Hansen (1905), Proudman (1953), Smith (1926), and need not be referred to here in complete detail.

Convenient schedules for the calculations have been set out by LaFond (1951) and these were used in this study.

Specific volume anomalies at standard depths for each of the hydrographic stations were first found. From them the geopotential anomalies were calculated

by summation. In turn the geopotential anomaly gradients between adjoining hydrographic stations were obtained and substituted in the Sandström-Helland-Hansen equation below, to give the dynamic currents. Thus

$$V = \frac{10(\Delta D_A - \Delta D_B)}{L \cdot 2\omega \sin \phi}$$

where

- V = component velocity normal to interval in metres per second,
- $\Delta D_A - \Delta D_B$ = difference in anomalies of dynamic height at hydrographic stations A and B, in dynamic metres,
- L = distance between stations, in metres,
- ω = angular velocity of the earth, equal to 0.729×10^{-4} radians per second,
- ϕ = mean latitude of the hydrographic stations (47.3°N.).

The depth for zero gradient was arbitrarily assumed to be 400 m. In consequence, the calculated currents are actually currents relative to whatever currents may have existed at this depth.

At the two inshore hydrographic stations, where the water shallows to less than 400 m., specific volume anomalies were assigned throughout a fictitious water column extending to a depth of 400 m. by extrapolating the isosteres to the boundary of the section, as proposed by Helland-Hansen (1934). In some instances, where the direction of extrapolation was uncertain, the values for the extended column were taken to be the same as in the column of the adjoining station. The error involved in this approximation is not great.

DESCRIPTION OF THE VELOCITIES IN THE SECTION

Velocities throughout the section for the series of eight crossings are plotted in Figures 3 to 5. For each crossing the figures show velocities (in centimetres per second), inward and outward with respect to the gulf, on the horizontal axis, while the vertical axis shows depths (in metres). The four curves on each graph, with points suitably distinguished by the legend, refer to the four intervals into which the section is divided, numbering from the southwest end.

Relative volume transport through an interval between two depths is represented on these graphs by the area bounded by horizontal lines at the respective depths, the vertical axis, and the velocity curve. Where the boundary of the interval is a part of the sloping bottom, this representation will only be approximate.

CRUISE S-19 ON 25 APRIL 1954 (FIG. 3A)

The currents in this spring crossing were all weak, the strongest being but 8 cm./sec. In the upper 30 m. the currents were outward in all four intervals, averaging slightly over 5 cm./sec. with the maximum of 8 cm./sec. in the first interval. This was the smallest maximum in the series of eight crossings described in this paper. In the first interval the outward current decreased uniformly from 8 cm./sec. at the surface to zero at a depth of 75 m. In the second interval, the

current decreased uniformly from 7 cm./sec. outward at the surface to zero at 60 m. depth. Below this, the velocity was inward increasing to 8 cm./sec. at 150 m., then decreasing to zero at 400 m. in a linear manner. In the third interval there was an outward current of 4 cm./sec. at the surface and an inward current of 3 cm./sec. from 50 to 75 m., decreasing to zero at 120 m. Below this there was a slight outward current. Throughout the fourth interval, the velocity was outward, increasing from 4 cm./sec. at the surface to 7 cm./sec. at 50 m., and below gradually decreasing to zero at 300 m.

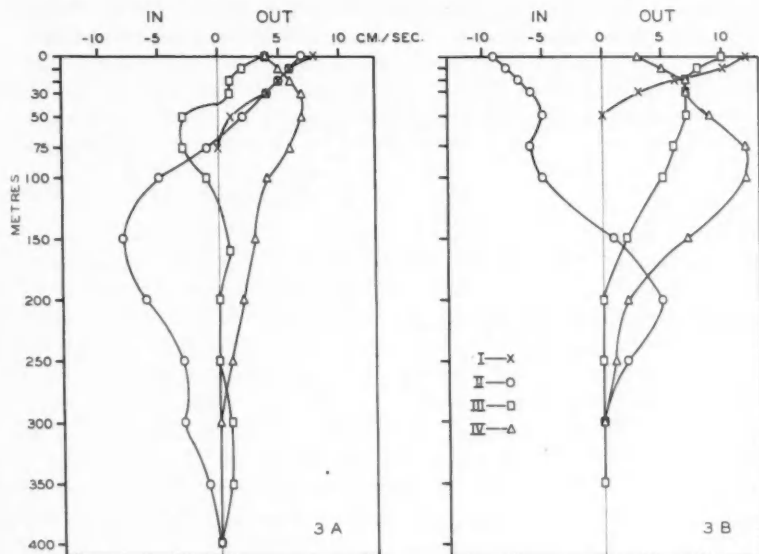


FIG. 3.—Velocity-depth curves for the Cabot Strait section from cruises S-19 (A) and S-7 (B).

CRUISE S-7 ON 15-16 MAY 1952 (FIG. 3B)

Velocities in this crossing were also low. In the first interval the velocity at the surface was 12 cm./sec. outward and was the maximum for this crossing. It fell gradually to zero at approximately 50 m. depth. In the second interval, inward flow was found. This is an unusual feature, observed only in this single cruise. This current decreased from 9 cm./sec. at the surface to 6 cm./sec. at 75 m. and to zero at 150 m. Below this, the velocity was outward, being 5 cm./sec. at 200 m. and zero at 300 m. Velocity in the third interval decreased gradually from 10 cm./sec. outward at the surface to zero at 200 m. In the fourth interval the velocity was outward. It increased from 3 cm./sec. at the surface to 12 cm./sec. at 75 and 100 m., and then decreased gradually to zero at 300 m.

In these two spring crossings S-19 and S-7, there was no inward current observed on the Newfoundland side of the strait.

CRUISE WT-2 ON 29 AUGUST 1950 (FIG. 4A)

In this crossing of the section the Cape Breton current was most highly developed with a maximum value of 62 cm./sec. outward at the surface in the second interval and falling linearly to zero at 300 m. depth. Lesser outward velocities were found in the first interval: 25 cm./sec. at the surface, decreasing to zero at 40 m., below which slight inward flow was found. In the third interval, inward velocities were found, decreasing uniformly from 19 cm./sec. at the surface to zero at 300 m. On the Newfoundland side (the fourth interval), flow was outward at the surface averaging 6 cm./sec. in the top 30 m. Below this depth a weak inward current of 2 cm./sec. extended to a depth of 150 m.

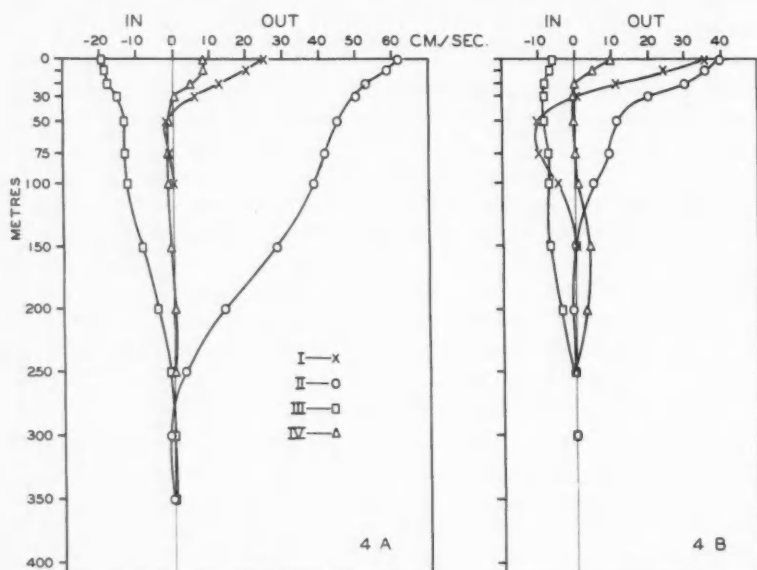


FIG. 4.—Velocity—depth curves for the Cabot Strait section from cruises WT-2 (A) and S-10 (B).

CRUISE S-10 ON 28-29 AUGUST 1952 (FIG. 4B)

This crossing was similar to the previous August crossing. The Cape Breton current was strong, and outward current also flowed at the surface on the Newfoundland side. In the first interval an outward velocity of 36 cm./sec. at the surface decreased uniformly to zero at 30 m. depth. Below this, there was an inward velocity averaging 10 cm./sec. in the range 50 to 100 m. and falling to zero below 150 m. In the second interval, the velocity was outward throughout, with a surface maximum of 40 cm./sec. reducing to 12 cm./sec. at 50 m. and to zero at 150 m. An inward current was formed in the third interval extending from the surface to 150 m. at an approximately uniform strength of 7 cm./sec. In the

fourth interval, a weak surface current of 10 cm./sec. was reduced to zero at 20 m., below which there was little flow in this interval.

CRUISE S-16 ON 29-30 OCTOBER 1953 (FIG. 5A)

A marked feature of this crossing was the strong Newfoundland current in the fourth interval resulting in a net inward transport in the whole section. The velocity in the first interval was outward, 25 cm./sec. at the surface and falling linearly to zero at 60 m. depth. In the second interval, the velocity was slight throughout, being 5 cm./sec. outward at the surface, zero at 30 m., and averaging 3 cm./sec. inward from 100 to 250 m. The third interval had a maximum outward velocity of 25 cm./sec. at the surface. This was reduced linearly to zero near the 250-m. level. In the fourth interval the velocity was strong and inward throughout, being 40 cm./sec. in the upper 30 m. Below this there was a uniform decrease to zero at 250 m.

CRUISE S-12 ON 2 NOVEMBER 1952 (FIG. 5B)

In this crossing there was a strong Cape Breton current comparable with that of the summer cruises and little inward flow on the Newfoundland side at the surface. In the first interval velocity was outward with a constant strength of 25 cm./sec. to a depth of 50 m. Below this the velocity decreased uniformly to zero at 250 m. The velocities of the second interval were outward and of a maximum strength of 60 cm./sec. at the surface. The decrease from the surface was approximately exponential with a reduction to half value in each succeeding 30 m. In the third interval the velocity was very small throughout, and of changing direction. In the fourth interval, at the surface, there was a small inward velocity which increased with depth to 15 cm./sec. in the 75- to 100-m. depth range, and then decreased gradually to zero at 350 m.

CRUISE WT-5 ON 8-9 NOVEMBER 1950 (FIG. 5C)

This cruise differed markedly from the other three autumn cruises, showing extremely small velocities throughout the section. In the first interval velocities ranged from 12 cm./sec. outward at the surface to zero at 100 m. depth. In the second interval the velocity at the surface was outward and only 5 cm./sec. It decreased to zero at 50 m., below which the velocity was inward averaging 4 cm./sec. from 50 to 300 m. The third interval velocities were all outward decreasing linearly from 16 cm./sec. at the surface to zero at 400 m. Velocities in the fourth interval were outward and averaged 5 cm./sec. in the upper 50 m. (Data for hydrographic station 38 were lacking below 50 m.).

CRUISE S-3 ON 11-12 NOVEMBER 1951 (FIG. 5D)

In the first three intervals of this crossing the velocities were outward showing a well developed Cape Breton current, while in the fourth interval there was a weak inward current extending to depth. The first interval velocities were constant in the upper 50 m., averaging 27 cm./sec. Below this the velocity decreased uniformly to zero at 150 m. Velocities in the second interval were out-

ward and decreased uniformly from a surface maximum for the section of 44 cm./sec. to 7 cm./sec. at 75 m. Below this the decrease was more gradual, reaching zero near a depth of 250 m. In the third interval velocities were outward and decreased from 13 cm./sec. at the surface to zero at 300 m. The velocities of the fourth interval were inward and weak, with a value of 3 cm./sec at the surface, 6 cm./sec. at 75 m., and zero at 200 m.

VOLUME TRANSPORT

Volume transport for this section of Cabot Strait was calculated from the velocity distribution for the eight crossings. Table III presents in columns 3 and 4 the transport out of (+) and into (−) the gulf, and in column 5 the net transport for each crossing. Mean values of transport for the spring, summer and autumn seasons are also given in the lower series of this table. Column 6 shows the velocity adjustment in centimetres per second which, applied uniformly over the whole section of the strait, would result in approximate zero net transfer. The velocity adjustment is the quotient of the net flow and the area of the section (35×10^6 sq. m.).

The transport due to the runoff of the St. Lawrence River at Quebec is 1.04×10^4 cu. m./sec. (Parde, 1948). In addition, the rivers below Quebec contribute approximately 0.3×10^4 cu. m./sec. (L. Lauzier, private communication). The mean rainfall over the Gulf of St. Lawrence, taken as 3 inches per month, is 0.6×10^4 cu. m./sec.; while the mean evaporation rate of approximately 75 cm. per year from the Atlantic Ocean in the vicinity of latitude 48°N . (Wüst, 1936) represents an evaporation of 0.5×10^4 cu. m. of water per second from the area of the gulf.

The average transport (outward) due to these three factors is thus:

Runoff	1.3×10^4 cu. m./sec.
Rainfall	0.6×10^4 cu. m./sec.
Evaporation	-0.5×10^4 cu. m./sec.
Total	1.4×10^4 cu. m./sec.

TABLE III.—Transport through Cabot Strait.

Column:		3	4	5	6
Cruise No.	Date	Transport			Velocity adjustment for zero volume transport
		Outflow (+)	Inflow (−)	Net	
		<i>million cubic metres per second</i>			<i>cm./sec.</i>
S-19	25 Apr. 1954	0.39	0.35	0.04	0
S-7	15-16 May, 1952	0.75	0.18	0.57	-2
WT-2	29 Aug. 1950	2.22	0.73	1.49	-4
S-10	28-29 Aug. 1952	0.71	0.50	0.21	-1
S-16	29-30 Oct. 1953	0.84	1.26	-0.42	1
S-12	2 Nov. 1952	1.26	0.72	0.54	-2
WT-5	8-9 Nov. 1950	0.55	0.29	0.26	-1
S-3	11-12 Nov. 1951	1.44	0.14	1.30	-4
Means	Spring	0.57	0.27	0.30	-1
	Summer	1.46	0.61	0.85	-2
	Autumn	1.02	0.60	0.42	-1

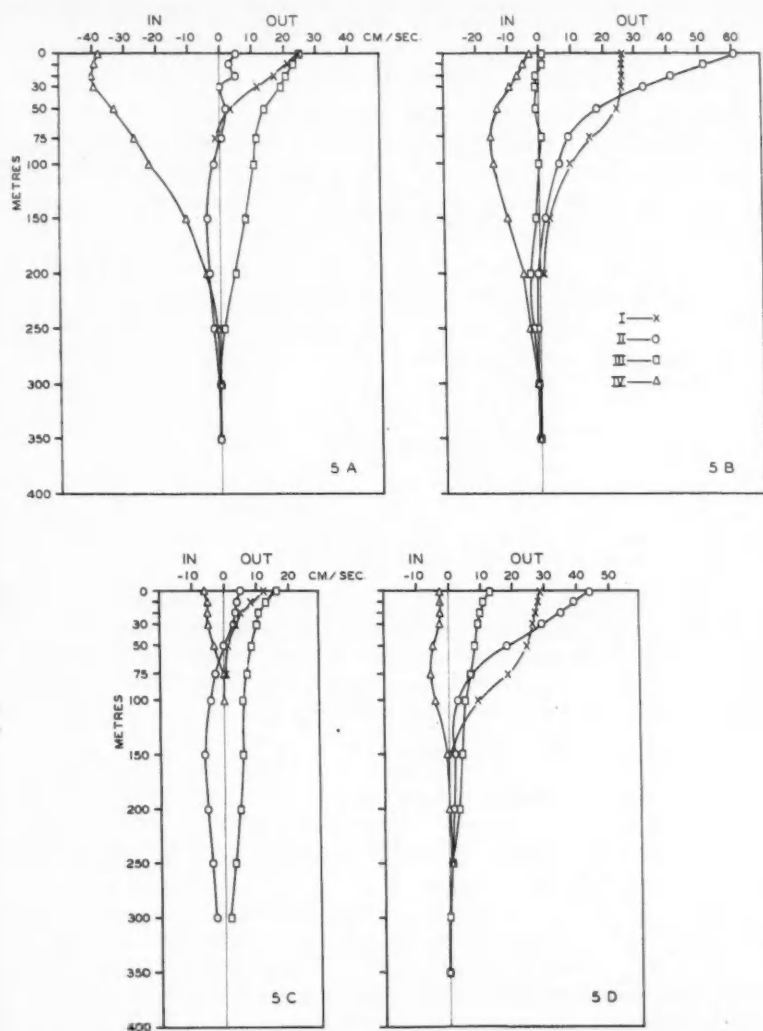


FIG. 5.—Velocity-depth curves for the Cabot Strait section from cruises S-16 (A), S-12 (B), WT-5 (C), and S-3 (D).

This transport is small compared to the observed net transports as found in column 5 of Table III and is of the order of the errors in the approximations, extrapolations, etc. made in carrying out the dynamic calculations.

The net transports of Table III are all outward except for cruise S-16. This suggests that a normal pattern of estuarine circulation exists, and a slow inward flow of dense water is to be expected at depth including the 400-m. level. The

reference level used in dynamic calculations would thus be one of slight inward motion.

TRANSPORT OF SALT

Transport of salt was calculated for the section for cruises S-3, S-16 and S-10. Table IV presents the results. The last column gives the velocity adjustment throughout the whole section to give zero salt transport. The agreement of these values with the corresponding adjustments for zero water volume transport in Table III is a partial check on the consistency of the data.

TABLE IV.—Salt transport and velocity adjustment for zero salt transport.

Cruise No.	Date	Salt transport	Mean salinities of section	Velocity adjustment for zero salt transport
		kg./sec.	‰	cm./sec.
S-10	28-29 Aug. 1952	6×10^6	33.7	-0.5
S-16	29-30 Oct. 1953	-15×10^6	33.5	1.2
S-3	11-12 Nov. 1951	42×10^6	33.1	-3.5

SUMMARY

1. Currents normal to four intervals across Cabot Strait are reported for eight crossings observing spring, summer and autumn conditions.

2. Accuracy of the current descriptions over the section is reduced through the assumption of the depth of 400 m. as that of zero motion, the extrapolations necessary at the sloping boundaries, and the loss of fine structure through limiting the section subdivision to four intervals only.

3. Features of the current in the strait as described by Dawson (1907) and Sandström (1919) were recognizable as generally true but varying greatly from season to season and cruise to cruise. The greatest flow was found in August and least in April and May cruises. In general, velocities were reduced to one-half surface strength at 75 or 100 m. depth.

4. Typical of the first (southwest) interval was an outward surface current which was reduced to zero at 50 to 75 m. depth. In the second interval strong outward currents at the surface were general, though the May 1952 cruise (S-2) offered an exception. In two of the autumn crossings inward currents were found below 50 m. depth in this interval. In the third interval the surface velocity was outward in the spring and autumn, but inward in the summer crossings. Velocities in the summer and autumn decreased uniformly with depth without reversal. In the fourth interval, the surface velocity was outward in the spring and summer crossings, increasing with depth to a maximum outward at 100 m. in the spring crossings, while, in summer, there was a slight inward flow below 30 m. In each of the autumn crossings, the velocity in the fourth interval was inward and extended to depth.

5. Net transport through Cabot Strait varied from 1.5 million cu. m./sec. outward to 0.4 million cu. m./sec. inward.

6. Estimate is made of the residual current at 400 m. and throughout the section which would result in approximate transport balance for Cabot Strait. This is found to be 4 cm./sec. at the greatest and for most crossings but 1 or 2 cm./sec.

Salt transport for several crossings are reported and are consistent with the mass transport variations.

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